VARIATIONS OF THE H AND K EMISSION LINES OF SINGLY IONIZED CALCIUM IN THE ECLIPSING BINARY STAR SYSTEM AR LACERTAE

BY

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TABLE OF CONTENTS

ACKNOWLEDGMENTS iv

LIST OF TABLES xii

LIST OF FIGURES xiii

ABSTRACT xiv

SECTION I A HISTORY OF OBSERVATIONS OF H AND K EMISSION AND THE AR LACERTAE SYSTEM 1
Prologue 1
Introduction 1
Early Observations of H and K Emission 2
Early Observations of AR Lacertae 4
Early Photometry 4
Early Spectroscopy 6
Correlation of Photometry and Spectroscopy 9
Early Polarimetry 9
The "AR Lac Group" and Other Stars with Ca II Emission 9
Further Observations of AR Lacertae 15
System Elements 15
Spectroscopy and Photometry 16
Radio Measurements 19
Polarimetry and Other Measurements 19
Summary 20

SECTION II INSTRUMENTATION AND OBSERVATIONS 30

Instrumentation 30
Telescope 30
Spectrograph 30
Plates 32
Sensitometer 33
Densitometers 33
Calculator 35
Observing Program 35

SECTION III DATA REDUCTION 40

Procedure and Theory 40
Plate-Tracing 40
Conversion of Deflections to Relative Intensities .. 43
Density-deflection relations: D(d) 43
Characteristic curves (D-log E curves): D(log E) and D(E) 44
Relative-exposure-deflection relations and relative-intensity-deflection relations: E (d) and I(d)..... 45
Relative plate speeds 46
Photographic normalization of relative intensities 46
Calculation of Equivalent Widths 47
Actual (absorption-plus-emission) line profiles .. 47
Emissionless profiles 49
The emissionless profile for the K star 49
Photometric scaling 54
The emissionless profile for both stars in combination 55
Further photometric scaling 56
The emissionless profile for the G star 56
Synthesized emissionless profiles 57
Profiles of the K-line emission 62
The equivalent widths of the K-line emission 62
Determination of error in the equivalent widths of the K-line emission 66

SECTION IV DISPLAY AND ANALYSIS OF REDUCED DATA 70

Data Display: The Graphical Relation 70
General Description 70
Eclipses of the Emission 73
Primary eclipse 73
Secondary eclipse 75
Comparison of primary and secondary eclipses 76
Extra-Eclipse Behavior 76
Interpretation of the Graphical Relation 77
Variability of the Emission 77
Relative Strengths of the Emission 77
Observed Surface Distribution of the Emission 79
Model for the Surface Distribution of the Emission . 81
Model for the Generation of the Observed Behavior of the Emission with Phase 83
Primary eclipse 83
Secondary eclipse 84
Extra-eclipse behavior 86
Anisotropic model 86

Temporal model 87
Spatial model 90
Conclusion 96
Correlations of Spectroscopy and Photometry 96
Eclipse correlation 97
Pre- and post-eclipse depressions 97
Distortion-wave-minimum--emission-maximum--period-change relation 99
Period changes 99
Distortion wave minimum and Ca II emission maximum 102
Conclusion 108
Summary 108

SECTION V GENERAL MODEL 111

Introduction 111
Spectroscopic Characteristics 111
Ca II Emission 111
Site of the emission 111
The chromosphere 112
An extended envelope 114
Gas streams 114
The tidal bulges 114
The entire stellar surface 115
Patches 116
Mechanism for and motion of the Ca II emission ... 117
Eruptive activity 118
Collisions and thermal gradients 118
Gas streams 123
Binary character 124
Conclusion 125
Depressions in emission 126
Magnetic fields 126
Other Spectroscopic Features 127
Hydrogen, cerium, iron and other metals 127
Radio emission 128
Photometric Characteristics 129
Introduction 129
Depressions in the light curve 129
Irregular Light-Curve Variations and the Photometric Distortion Wave 129
Pulsation as the agent 131
Ring, shell, or envelope as the agent 131
Gas streams as the agent 132
Starspots as the agent 132
Existence and observability of starspots 145
Conclusion 148
Period Changes 148
Introduction 148
Mass Loss as the Mechanism 149
Component Interaction as the Mechanism 152
Other Effects as the Mechanism 152

Correlations of Phenomena 153
Introduction 153
Spectroscopic-Photometric Correlation 153
Photometric-Infrared Correlation 155
Photometric-Radio Correlation 155
Luminosity Correlations 156
Conclusion 156
Evolution of Stars with Ca II Emission 156
Introduction 156
Stage of Evolution 157
Pre-main sequence 157
Post-main sequence 158
Circumstellar matter, component masses, and population count 160
Ca II emission and Li absorption 165
Ages of the RS CVn Systems 168
Other Evolutional Effects 169
Summary 170

SECTION VI FUTURE INVESTIGATIONS 176
Introduction 176
Spectral Analysis 176
Equipment 177
Observations 182
Epilogue 187

REFERENCES 188

BIOGRAPHICAL SKETCH 197

LIST OF TABLES

Table 1	GENERAL CHARACTERISTICS OF RS CVn BINARY STAR SYSTEMS AND PARTICULAR CHARACTERISTICS OF AR Lac	23
Table 2	RS CVn BINARY STAR SYSTEMS	29
Table 3	RELATIVE EQUIVALENT WIDTHS OF THE Ca II K-LINE EMISSION IN AR Lac	71
Table 4	PHASE OF AR Lac AT DISTORTION WAVE MINIMUM, EMISSION MAXIMUM, AND PERIOD CHANGE	105

LIST OF FIGURES

Figure 1	PROFILES OF THE Ca II K LINE IN AR Lac ...	51
Figure 2	CONSTRUCTION OF EMISSIONLESS PROFILES FOR THE Ca II K LINE IN AR Lac	52
Figure 3	VARIATION OF THE RELATIVE EQUIVALENT WIDTH OF THE Ca II K-LINE EMISSION WITH ORBITAL PHASE IN AR Lac	72
Figure 4	THE ENHANCED MIGRATION CURVE FOR AR Lac ..	107

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The variability of the Ca II emission and the association of any such variation with the photometric behavior and with other characteristics of AR Lac were the primary questions considered in this investigation. In pursuit of these objectives a series of spectrographic plates spanning the entire orbital cycle of AR Lac was obtained by the author during 1976-1977.

Reduction of the K-line emission data by photographic, photometric, and spectroscopic scaling revealed emission throughout the cycle and emission eclipses well-correlated in phase with the photometric eclipses. Also observed were (1) pre- and post-primary eclipse emission depressions followed and preceded, respectively, by pre- and post-primary eclipse emission increases, (2) pre- and post-secondary

eclipse emission increases, and (3) an extra-eclipse local emission maximum at phase 0.384.

The model constructed to account for these phenomena consisted of (1) permanent emission distributed over the entire stellar surfaces, (2) permanent emission regions located at the tidal bulges of the stellar components, (3) Ca II-absorbing circum-secondary material and (4) an isolated emission region temporary in surface or temporal location (a moving spot group or a flare, respectively).

The extra-eclipse emission maximum at phase 0.384 was discovered to be congruent with the migration curve for the photometric distortion wave minimum of AR Lac, as was another apparent extra-eclipse emission maximum recorded at a different epoch by a different observer. Data from yet another source revealed that at a still different epoch an extra-eclipse Ca II emission maximum coincided in phase with the photometric distortion wave minimum at that epoch. On the basis of these limited data an interrelationship of the Ca II emission, the distortion wave, and the period changes in AR Lac was therefore tentatively demonstrated.

A re-evaluation of contradictory reports regarding the visibility of individual starspots led to the conclusion that large spots would indeed be observable with equipment of high precision.

A comprehensive physical and evolutional model for the cumulative spectroscopic and photometric behavior of AR Lac was constructed by augmentation of other models and incorporation of the results of the present investigation.

SECTION I
A HISTORY OF OBSERVATIONS OF H AND K EMISSION AND THE AR LACERTAE SYSTEM

Prologue

The history presented herein is an approximate chronology of the observations which are pertinent to the present investigation. Because it is intended merely as a chronicle of observations, no extensive interpretation or discussion by the observers is presented; and only brief, bracketed comments are offered by the author. Detailed discussions are included in Sections IV, V, and VI.

Introduction

H and K emission, which is observed in the spectra of numerous late-type stars and stellar systems, has confounded astronomers for over a century. Prominent H and K emission is exhibited by the eclipsing binary system AR Lacertae, which has manifested itself as a puzzle of considerable complexity not only because of its strong emission but also because of its many other unusual characteristics. The history of astronomical observation of H and K emission began over a third of a century before AR Lacertae was detected as a variable and more than half a century before AR Lacertae was discovered to exhibit H and K emission.

Early Observation of H and K Emission

The H and K spectral lines are two of the solar lines which were alphabetically designated by Fraunhofer in 1814-1815 (Abell, 1964) when he rediscovered the myriad of dark (absorption) lines crossing the solar spectrum. The H and K lines are resonance lines of singly ionized calcium (Ca II).The H line, at wavelength 3968.47 A, is produced by the 4p $^2P_{1/2}^o$ - 4s $^2S_{1/2}$ transition; whereas the K line, at 3933.67 A, arises from the 4p $^2P_{3/2}^o$ - 4s $^2S_{1/2}$ transition (Shore and Menzel, 1968). The H line is usually blended with the H-epsilon line (3970.07 A) of the Balmer series of hydrogen.

The discovery of H and K emission in the spectrum of an astronomical object was made by Young (1872), who visually detected emission reversals at the centers of Ca II absorption lines in the sun (St. John, 1910). According to Young, the lines were observed to be "regularly reversed on the body of the sun itself, in the penumbra and the immediate neighborhood of every important spot" (St. John, 1910, pp. 36, 37). Four years later, Draper made the first photograph of the solar spectrum (Smithsonian, 1978). The first photographic plates of the spectra of sunspots, obtained in 1883 by Lockyer, revealed H and K emission reversals over the spots. Subsequent plates obtained in 1886 and 1887 by Rowland exhibited both single and double reversals. Hale's plates taken in 1891 demonstrated that the reversals are not confined to the vicinity of sunspots,

but are instead found "in regions irregularly distributed over the entire disk of the sun" (St. John, 1910, p. 37). Hale's plates showed the double reversal of the H and K lines reported by Rowland: a broad absorption feature (which Hale termed H1 or K1) upon which is superposed an emission line (H2 or K2) with a narrow absorption line (H3 or K3) at its center.

Emission reversals at the centers of absorption lines of stellar spectra were first observed in 1900 by Eberhard and Ludendorff, who detected an emission core in the Ca II K line on a "very strongly overexposed" (Eberhard and Schwarzschild, 1913, p. 292) spectrum of Arcturus. Engaging in further investigation of the phenomenon, Schwarzschild recorded H and K emission reversals on spectral plates of Arcturus, Aldebaran, and sigma Geminorum in 1913. By comparison of the strength of the stellar emission to that of the average spectrum of the sun, Eberhard and Schwarzschild concluded that "the emission is much stronger in these stars than in the sun" (Eberhard and Schwarzschild, 1913, p. 294). They stated further that "reversals of lines in stellar spectra are not rare" (Eberhard and Schwarzschild, 1913, p. 294).

By 1929 a veritable multitude of other stars, such as Capella and epsilon Pegasi, had been discovered to exhibit H and K emission superposed on absorption. Others, such as Arcturus, Antares, and Betelgeuse, were discovered to have a complex double reversal of the H and K lines similar to that

found in the sun (Adams and Joy, 1929a,b). A correlation between emission strength and absolute magnitude was discovered by Deslandres and Burson (1921, 1922), "the more luminous giants having stronger emission lines" (Adams and Joy, 1929b, p. 373).

Early Observations of AR Lacertae

Early Photometry

AR Lacertae was discovered to be variable by Leavitt (Leavitt, 1903; Pickering, 1907a; Sahade and Wood, 1978). For the next twenty years, though, its variability seemed questionable, being confirmed by some observers (Pickering, 1907b; Munch, 1909; Wendell, 1913) and denied by others (Hoffmeister, 1919; Zinner, 1922).

By obtaining a visual light curve from analysis of his observations made in 1927 and 1928, Loreta (1929) first recognized AR Lac as an Algol-type system with a period of $1^{d}.98$. By his own observations and by analysis of Loreta's (1929) and Wendell's (1913) observations, Jacchia (1929) confirmed Loreta's analysis of AR Lac as an eclipsing binary.

The first photographic light curve of AR Lac was published in 1931 by Rugemer (1931). In the following year Schneller and Plaut (1932) published a second light curve. These three investigators calculated the apparent visual magnitudes and the relative sizes and luminosities of the components, the orbital inclination, and a more precise value for the period of the system. Their data also

established that the cooler star eclipses the hotter one at primary eclipse, which is total. In addition, the depths of the minima at both eclipses were determined. Application of their photometric results to the HD Catalogue spectral classification (G5), which they suspected might be a composite, allowed rough determinations of the spectral classes of the components as either G5 and K5 or G0 and K0 for the smaller and the larger stars, respectively (Schneller and Plaut, 1932; Harper, 1933).

From his photometric observations Himpel (1936) classified AR Lac's components as G5 and gK5, the luminosity class of the cooler star having been determined from its surface brightness. In the light curve he noted a bump during totality (primary minimum).

The first photoelectric observations of AR Lac (Sahade and Wood, 1978), made in 1938 and 1939 by Wood (1946), enabled him to complete his solution of the orbit in 1941. (Publication of his dissertation was delayed until 1946 because there was "a small war on then": Wood, 1983.) He determined that between the time of earlier observations by Dugan and Wright and the time of his own observations, the period of the system had undergone an abrupt change, thereby necessitating the calculation of new orbital elements. From light-curve variations which occurred only outside primary minimum, Wood (1946) inferred that the brighter (G5) component is variable. Although it was later discovered (Blanco and Catalano, 1970) that Wood's

comparison star, HD 209813 (HK Lac), is a variable, Wood's observations were not invalidated, because he had compensated in his data reductions for what he termed "large night errors" (Wood, 1946, p.13). His results are therefore quite harmonious with more recent observations using nonvariable comparison stars.

While attempting to measure the limb darkening coefficient of the K0 component of AR Lac, Kron serendipitously discovered "small abrupt irregularities" (Kron, 1947, p. 264) in the light level during primary minimum ingress and egress, thereby complementing Wood's (1946) observations of anomalous photometric variations only outside primary minimum. Kron interpreted his observations as Wood had interpreted his: viz., that the primary star (G5 star) is intrinsically variable. Kron also reported several observations of strong asymmetry between minima. Comparison of data from several epochs showed variability of the asymmetry and variability of the skewness of secondary minimum. Prominent ellipticity and reflection effects were evident, as was a "very high degree" (Kron, 1947, p. 264) of limb darkening for the K0 star.

Early Spectroscopy

Spectrograms obtained in 1932 by Harper revealed AR Lac to be a double-line spectroscopic binary. He made an attempt to classify the spectral types of the components more precisely, but was not entirely successful because clouds precluded his obtaining any plates at primary

minimum, when the spectrum of the cooler component alone would have been visible. He did, however, publish the first radial velocity curves for the system and was able to establish the spectroscopic elements within "reasonable agreement" (Harper, 1933, p. 148) with the previous photometric elements determined by the three Germans. His analysis determined that the masses of the components are very nearly equal, the larger star ($1.42M_{\odot}$) being only $0.01M_{\odot}$ more massive than the smaller more luminous one. He found the lines of the primary to be sharper than those of the secondary. The three-to-one disparity in the relative luminosities of these components of almost equal masses and very similar spectral types (G5 and G2, respectively, by his spectrograms) caused Harper to express some puzzlement.

The discovery of H and K emission reversals in AR Lac was announced by Wyse (1934). He had detected sharp emission cores in the broad H and K absorption lines in the spectrum of the cooler component. He classified the spectra of the components as G5 for the brighter and K0 for the fainter. The luminosity class of the primary (brighter) was ascertained to probably be main sequence, whereas the luminosity and the density of the secondary placed it intermediately between the main sequence and the giants.

Joy and Wilson (1949) tabulated previously unpublished data obtained by Sanford (1951), who had discovered in 1945 that Ca II emission is present not only in the AR Lac secondary but also in its primary. They listed the

spectral-luminosity classifications of the components as sgG5 and sgK0, the luminosity class of the primary heretofore having not been explicitly specified except for Wyse's (1934) tentative main-sequence classification.

New spectroscopic elements for AR Lac were published in 1951 by Sanford (1951), whose data indicated that the orbit is circular. The spectra showed the absorption lines to be very broad and shallow for such late-type stars, a characteristic which he ascribed to the lines' being appreciably broadened by synchronous rotation. Measurements of the equivalent widths of the Ca II emission (H2 and K2) and the underlying absorption (H1 and K1) for each component showed the emission contributions from both stars to be variable with phase. Additionally, the ratio of the primary's to the secondary's emission increased from phase 0.0 to 0.5 and decreased from phase 0.5 to 1.0. Radial velocities computed from the emission lines were 6.4 km/sec less than those from the absorption lines. Assuming that the breadth of the Ca II emission indicates that it emanates from all parts of the stellar surfaces or from complete equatorial zones, Sanford calculated the radii of the components to be about 85% of the value determined by Wood, who had included a large coefficient of limb darkening. Sanford's measurements indicated the masses to be 1.3 $M_{\odot}$ and 1.31 $M_{\odot}$ for the primary and the secondary, respectively.

Using spectra obtained in 1954, Roman (1956) noted the presence of H and K emission and classified the spectrum of AR Lac as K2 III at primary eclipse and K2 III + F8 at secondary eclipse, her results confirming yet again that no two observers obtain exactly the same results for AR Lac.

Correlation of Photometry and Spectroscopy

From the photometric elements of AR Lac and Sanford's (1951) spectroscopic data, Eggen (1955) derived the absolute visual magnitudes, the masses, and the radii of the components.

While analyzing several systems with light-curve variations not explainable by tidal effects, the reflection effect, or eclipse, Kron (1952) noted a rotational periodicity of these photometric variations in AR Lac, RT And, RS CVn, and YY Gem. He further observed that all four systems exhibit emission lines. In YY Gem, changes in the Ca II emission strength were observed to show a pattern of amplitude and period behavior similar to that of the light-curve variations.

Early Polarimetry

Seeking to measure the polarization of the H and K emission in AR Lac, Struve (1948) obtained null results; but he was able to establish an upper polarization limit of 10% for the system.

The "AR Lac Group" and Other Stars with Ca II Emission

In his study of spectra of eclipsing binaries, some displaying Ca II emission, Wyse noted an "unexpected

tendency" (Wyse, 1934, p. 41) for late-type secondaries to exhibit hydrogen emission.

Swings and Struve (1941) and Struve (1945) investigated stars which exhibit late-type absorption features combined with bright lines of high excitation. Struve (1945) observed that "in single stars emission lines are rare for these types [A through K]" (Struve, 1945, p. 79); whereas "binaries of types G and K very often exhibit bright lines of Ca II, and the number of these cases is also considerably in excess of what might have been expected from the frequency of occurrence of these lines in single stars" (Struve, 1945, p. 79).

Upon surveying emission-line stars again, Struve (1946) recognized a fledgling group of binaries characterized primarily by bright lines of Ca II. Additional identifying features of this grouping were (1) spectral type usually later than F5, (2) resemblance of the emission lines to those of normal single K-type dwarfs, (3) usually single or slightly broadened lines, which are (4) superposed on deep, broad Ca II absorption, and are (5) usually visible throughout the cycle, but in some systems are strengthened at primary minimum or weakened at secondary minimum.

A list of 445 stars and star systems known to exhibit Ca II emission, published by Joy and Wilson (1949), verified Eberhard and Schwarzschild's (1913) suspicion that H and K emission is not a rare phenomenon in stars. Joy and Wilson's comparison of intensity levels at various parts of

each spectrum showed that although the emission is usually much weaker than the local continuum, the broad H and K absorption is so strong that it provides a low-intensity background against which the faint emission is easily observed. Visual comparison of emission in stars of the same spectral-luminosity type produced no correlation between emission strength and any other physical characteristics. At the dispersions used they noted no H3 or K3 in subgiants or dwarfs. In the sun, giants, and supergiants, they observed the red component of the emission (the red component of H2 and K2) to be more intense than the violet. Further, they stated that the emission intensity is probably variable in many stars.

A new decade dawned with Gratton's review of characteristics of stars which exhibit Ca II emission. He opened his discussion by stating that for late-G or early-K binaries "these emission lines are much stronger than those observed in single late-type stars such as alpha Boo [spectral class K2 (Abell, 1964)], being real emission lines rather than a reversal of the absorption lines" (Gratton, 1950, p. 31). [However, the author can find no previous statement of this assertion, or any reports of observations substantiating this statement, not even in the very references from which Gratton purportedly obtained this information. Perhaps he misread or misunderstood Struve's (1945) statement regarding the <u>frequency</u> of occurrence of the emission, not the <u>strength</u> of the emission.] Gratton

discovered a period-luminosity relation for binaries with Ca II emission.

Tables of quantities for 426 stars whose spectra exhibit H and K emission lines were published in 1954 by Bidelman, who repeated Gratton's (1950) assertion, though not quite so positively: "The Ca II emission lines are probably stronger in binaries than in single stars" (Bidelman, 1954, p. 178). [Perhaps his compendium of references would offer supporting evidence; however Gratton (1950) is among them . . .] Bidelman also noted from his survey the likelihood that all late-type giants exhibit some, "usually self-reversed" (Bidelman, 1954, p. 178), Ca II emission and that there exist some "surprising variations in intensity" (Bidelman, 1954, p. 178) among stars of the same spectral class.

Spectrograms of the Fraunhofer lines obtained by McMath et al. revealed that in the solar H and K lines (1) the line intensity was similar between the disc and the chromospheric bulge, and (2) the line cores were observed to "merge smoothly with the chromospheric emission bulge" (McMath et al., 1956, p. 7) as the limb was approached. In addition, asymmetry of the emission profile persisted to the limb; and the K emission was enhanced over plages.

Measurements of the H and K emission lines in the sun by Wilson and Bappu (1957) showed them to be of nearly equal width and of intensity ratio 1:2. Stellar evidence, though not conclusive, seemed to indicate a similar picture.

Enlarging upon the work of Adams and Joy (1929a,b), Wilson and Bappu discovered a relationship between emission-line width and absolute magnitude. In G, K, and M stars the K-line emission width varies as the one-sixth power of the absolute luminosity, the emission-line width being independent of spectral class and emission-line intensity. This relationship has become known as the Wilson-Bappu effect.

While investigating single stars, visual binaries, and galactic clusters with H and K emission, Wilson (1963) observed that the spectroscopic binary component in each of two visual binaries (ADS 2644 and ADS 8119) exhibits a preponderance of Ca II emission compared to its single visual companion. In addition, he noted that in the sun a strong correlation exists between the local chromospheric magnetic field and the intensity of the Ca II emission, a condition which he inferred could obtain in other stars also.

At Lick Observatory, spectroscopy by Preston and simultaneous UBV photometry by Kilston showed that the Cepheid-like variable BL Her exhibited "well-marked emission lines of hydrogen and Ca II for about 2^h during rising light" (Lick, 1966, p. 779) and that "the emission and the atmospheric velocity reversal occur during a still-stand on the light curve" (Lick, 1966, p. 779).

Oliver (1971, 1974) tendered the suggestion that AR Lac and similar systems belong to a group characterized by (1)

Ca II emission, (2) a K0 subgiant secondary which does not fill its Roche limiting surface, (3) a mass ratio near 1.0, and (4) light-curve variations which are attributable to the cooler component. He proposed that this group be designated the RS Canum Venaticorum binary systems. In his investigations he discovered that several members of the group exhibit (1) asymmetries in their light-curve minima and shoulders and (2) a photometric "quasi-sinusoidal distortion wave" (Oliver, 1974, p. 252), comprising nearly sinusoidal extra-eclipse variations which migrate epoch by epoch toward earlier phase.

The discovery of "significant variations" (Weiler, 1975, p. 1) in the H and K emission-line intensities of several RS CVn systems was announced by Weiler (1975, 1978). For three of the systems (UX Ari, RS CVn, Z Her) he further determined that the maximum of emission intensity and the minimum of the photometric distortion wave coincide in orbital phase. In AR Lac he found the emission variations to be basically random.

In an extensive review of the observational properties of the RS CVn binary systems (and other related systems), Hall (1976) proposed a working definition [reminiscent of Oliver, 1971, 1974] composed of those observational characteristics exhibited by all twenty-four systems so far identified as belonging to the group. [For a list of these characteristics as they apply to AR Lac, see Table 1.] Members of one of the related groups of stars exhibit flare

activity, which Hall proposed may occur in RS CVn stars also, but go unobserved because of their greater intrinsic luminosities.

Late in the following year, Young and Koniges (1977) published the results of their study of the Ca II emission and other spectral characteristics of late-type binaries [AR Lac was not included]. They found that systems with periods near 20 days typically have the strongest Ca II emission. Popper's evidence (1977) had shown that the emission is strongest when one of the components is evolved. Young and Koniges determined that both the strength of chromospheric emission and the strength of tidal coupling are directly related to the ratio of the radius of the star to its Roche lobe. As for other spectral characteristics, their spectrograms showed no emission in the Na D lines and no strong Li I (6708 A) line for any of the systems. [The latter characteristic is of interest because it is apparently an age discriminator. See Section V.] Complementing the findings of Young and Koniges, Naftilan and Drake (1977) observed no evidence of Li 6708 in AR Lac either.

Further Observations of AR Lacertae

System Elements

In attempts to improve mass determinations in binary systems Popper (1967) acknowledged AR Lac as being the only subgiant system with well-determined masses, which he calculated as $1.32 \pm 0.06 M_{\odot}$ and $1.31 \pm 0.07\ M_{\odot}$ for the

primary and the secondary, respectively. He quoted the radii as 1.8 $R_{\odot}$ and 3.0 $R_{\odot}$, respectively, adding that they are less well-determined than those of the components of other systems.

V - R photometry of AR Lac (and other binaries) by Lacy (1979) allowed a new determination of its mass, radius, absolute magnitude, and distance. He determined that the primary of the system is underluminous compared to his theoretical zero-age main sequence.

Spectroscopy and Photometry

Three-color photometry of AR Lac in 1972, 1973, and 1974 by Chambliss (1976) produced a new set of photometric elements, from which the effective temperatures of the primary and the secondary were calculated to be compatible with spectral-luminosity classes G2 IV and K0 IV, respectively. In the light curve Chambliss observed an 0.04-mag intrinsic photometric variation (Chambliss, 1975a,b; 1976) which shifted in phase from season to season (Chambliss, 1976), behavior which constituted a photometric distortion wave (Chambliss, 1975b; Hall, Richardson, and Chambliss, 1976). The wave was later discovered to be varying in amplitude (0.04-0.1 mag) and migrating toward decreasing orbital phase (Hall, Richardson, and Chambliss, 1976). Chambliss' (1976) data also indicated that the coefficient of limb darkening is low for the primary and high for the secondary. Attempts to correlate optical variability with radio outbursts yielded null results.

Babaev (1974a,b,c,d; 1975a,b; 1976) published seven papers dealing with spectroscopy and photometry of AR Lac. From his radial velocity curves he derived revised spectroscopic elements. His profiles for the H and K lines exhibited changes in the emission reversals during ingress, egress, and eclipse. Measurements of the equivalent widths of the H and K lines showed variation throughout the orbital cycle and a pronounced absorption maximum at phase 0.6489. His three-color light curves exhibited irregularities within as well as outside of eclipse.

Supplementing Babaev's work, Weiler (1975, 1978) further investigated AR Lac's migrating photometric distortion wave and its emission-line intensity variation with phase. He could discern no correlation between the two phenomena, and his observations showed "basically random" (Weiler, 1978, p. 77) emission intensity variation.

Hall, Richardson, and Chambliss (1976) discovered by reviewing data obtained by previous observers that the photometric distortion wave of AR Lac migrates toward decreasing orbital phase and that the migration rate is not constant, but instead has varied smoothly from one cycle every 50 or 60 years to one cycle every 10 or 15 years. The grand climax of their work was the discovery of a relationship which could be used to predict the epochs of future period changes in AR Lac. Graphs of (1) orbital phase of the migrating photometric distortion wave minimum versus epoch and of (2) orbital phase of the photometric

distortion wave minimum at which period changes have occurred versus epoch appeared to coincide. Period decreases occurred when the wave minimum was at phase 0.25; increases, at 0.75.

Moderate metal underabundances in both components of AR Lac were measured by Miner (1966), who reported that all eclipsing binaries so far measured had been found to be metal poor.

Naftilan and Drake (1977) determined that the displacements of the emission cores from the centers of the Balmer lines of the AR Lac secondary component are symmetrical about the absorption-line centers. Rapid changes in the emission profiles over very short time intervals were also observed. Their spectra showed further that the emission-line broadening for both stars is consistent with that of synchronous rotation, and that for all the stronger emission lines the emission of the secondary is much stronger than that of the primary. The secondary was found to be moderately metal-deficient; whereas the primary was found to have normal solar abundances, Miner (1966) notwithstanding. In addition, the microturbulence velocity for the secondary was found to be anomalously high for a subgiant, being more in keeping with values usually observed in supergiants. That for the primary was relatively high also.

Radio Measurements

Hjellming and Blankenship (1973) announced their discovery of variable radio emission from AR Lac at 2695 MHz and 8085 MHz.

Further radio observations of AR Lac by Owen and Spangler established an upper angular limit of about 1" on the size of the radio emitting region and a lower volume limit of "much larger than the stars in the system" (Owen and Spangler, 1977, p. L43), the latter being determined by the failure of a clearly defined eclipse to appear in the radio emission. Their data exhibited no evidence of the previously deduced circular polarization of the radio emission.

In 1978 Feldman (1978) reported the observation of a large radio flare in AR Lac.

Polarimetry and Other Measurements

Measurements of V- and R-band polarization in binary systems by Pfeiffer and Koch (1977) indicated that AR Lac displays polarization which is constant and no different from that of the interstellar medium. No results were available for tests to determine (1) the shape of AR Lac's polarization spectrum compared to that of the interstellar medium or (2) the variability of AR Lac's electric vector with wavelength.

An infrared excess was measured for AR Lac by Atkins and Hall (1972), and an ultraviolet excess which increases with decreasing wavelength below 4600 A was discovered by Rhombs and Fix (1977).

Continuing to demonstrate that it is no ordinary system, AR Lac apparently underwent further period changes in 1975 as evinced by observations of minima from 1973-1976 by Scarfe and Barlow (1978) and in 1977 by observations of minima from 1960-1982 by Nha et al. (1982). [Neither observation is included in Table 4 or in Figure 4.] Soft x-rays were detected emanating from AR Lac by Walter (1978). Observations by Nha and Kang (1982) indicated that the K0 star may exhibit long-term light variations. The amplitude of AR Lac's migrating photometric distortion wave increased to 0.1 between 1978 and 1979 (Hall, 1980). During this period of time the wave also migrated extremely quickly, changing position by 0.4 phase units (Hall, 1980). The minimum of the photometric distortion wave was at about phase 0.9 in 1979, and the amplitude of the distortion wave was very low--less than 0.01 mag (Caton, 1981).

Summary

The presence of H and K emission occurs with great frequency in late-type (G, K, and M) stars. It is apparently observed in all types of binaries more frequently than in single stars. In some close binaries the emission is much stronger than in single stars, but whether this holds as a general rule has not been verified.

In the sun the ratio of the strength of H to K emission is 1:2, a condition which evidence suggests may exist in other stars also. H3 and K3 are observed only in the sun, giants, and supergiants. In these stars the red component

of H2 and K2 is more intense than the violet. A correlation was reported between emission strength and absolute magnitude, the more luminous giants having stronger emission lines. This discovery has been superseded by the more recent discovery of a more accurate relationship--that between Ca II emission-line width and absolute magnitude in G, K, and M stars. This relation is expressed by the Wilson-Bappu effect: viz., that the K-line emission width varies as the one-sixth power of the absolute luminosity. The emission-line width is independent of both spectral type and emission-line strength. There appears to be no correlation between emission strength and any other physical characteristics of stars of the same spectral-luminosity class.

In many stars the emission intensity is variable outside eclipse, and the emission undergoes eclipse as the stars revolve. In some cases there is an enhancement of emission at primary minimum and a diminution of emission at secondary minimum.

Evidence indicates that the solar correlation between chromospheric magnetic field strength, Ca II emission intensity, and plages and sunspots may obtain in other stars also. In binary systems there seem to be direct relationships between the strength of chromospheric emission, strength of tidal coupling, and the ratio of the radius of the star to its Roche lobe, and between the strength of chromospheric emission and the evolutional stage

of the star. Stronger emission correlates with a more advanced evolutional stage.

Many of the binary systems which exhibit H and K emission also exhibit asymmetry and irregular fluctuations in their light curves.

Virtually all the eclipsing binaries for which abundances have been measured exhibit metal deficiencies.

AR Lacertae is a typical RS Canum Venaticorum binary star system. In excess of 25 such systems have been discovered; all but three are eclipsing binaries. Table 1 lists the characteristics of RS CVn systems in general and of AR Lac in particular. Table 2 lists the currently known RS CVn systems and some of their vital statistics.

Table 1
GENERAL CHARACTERISTICS OF RS CVn BINARY STAR SYSTEMS
AND PARTICULAR CHARACTERISTICS OF AR Lac

The RS CVn systems form a class of spectroscopic binaries which are distinguished by three characteristics (Oliver, 1974; Hall, 1976):

(1) The orbital period is between 1^d and 14^d.
(2) The hotter component is of spectral class F or G and of luminosity class IV or V.
(3) Spectra at phases outside eclipse exhibit strong Ca II H and K emission. ("Strong" is defined to mean stronger than the normal H and K emission reversals in late-type single stars of the same spectral class.)

AR Lac fulfills these three defining criteria for membership in the RS CVn classification:

(1) It has an orbital period of $1^d.983$ (Loreta, 1929).
(2) The spectral-luminosity class of its hotter component is G2 IV (Chambliss, 1974).
(3) The system exhibits strong H and K emission at phases outside eclipse (Wyse, 1934; Sanford, 1951).

There are a number of other characteristics which AR Lac has in common with varying numbers of the other RS CVn systems (Hall, 1976). Spectral characteristics shared with many of the other systems are:

(1) The system is a double-line spectroscopic eclipsing binary (Harper, 1933).
(2) The H and K emission is from the cooler star or from both stars. The latter is the case for AR Lac (Sanford, 1951).
(3) The spectral-luminosity class of the cooler component is close to K0 IV. The secondary of AR Lac is classified K0 IV (Wyse, 1934).
(4) The system exhibits H-alpha emission outside eclipse (Weiler, 1975, 1978).
(5) The system exhibits an infrared excess in one or both components. It is observed in both components of AR Lac (Atkins and Hall, 1972).
(6) The system exhibits an ultraviolet excess. In the ultraviolet AR Lac is too bright by an amount which increases with decreasing wavelength below 4600 A (Rhombs and Fix, 1977).
(7) The system exhibits radio emission (Hjellming and Blankenship, 1973).

Photometric characteristics which AR Lac has in common with one-third to one-half of the other RS CVn systems are:

(1) The light curve of the system exhibits an extra-eclipse quasi-sinusoidal wave-like distortion (Chambliss, 1975b) which migrates toward decreasing phase (Chambliss, Hall, and Richardson, 1975).

Table 1 - continued

(2) The depth of primary minimum is variable. This is a natural consequence of the distortion wave (Hall, 1976).

(3) The displacement of secondary minimum (asymmetry) is variable. This is a natural consequence of the distortion wave (Hall, 1976).
   (a) no asymmetry observed (Taylor, 1941)
   (b) strong asymmetry (Wood, 1946)
   (c) variable asymmetry (Kron, 1947; Hall, 1976; Theokas, 1977).

(4) The light curve exhibits irregular variations (Wood, 1946; Kron, 1947; Babaev, 1971; Chambliss, 1975b; Hall, Richardson, and Chambliss, 1976; Hall, 1976).

Physical characteristics which AR Lac has in common with one-third to one-half of the other RS CVn systems are (Oliver, 1974; Hall, 1976):

(1) The mass ratio of the components of the system is near unity. For AR Lac it has been computed between 0.987 and 1.008 (Harper, 1933; Sanford, 1951; Wood, 1946; Kopal, 1958; Popper, 1967; Oliver, 1974; Babaev, 1975; Popper, 1976; Chambliss, 1976; Hall, 1976; Popper and Ulrich, 1977; Weiler, 1978).

(2) The system is detached; that is, neither component fills its Roche lobe (Wood, 1950; Kopal, 1958; Plavec and Grygar, 1965; Oliver, 1974; Chambliss, 1976; Morgan and Eggleton, 1979)

Orbital characteristics which AR Lac and a few of the other RS CVn have in common are:

(1) The system has a varying orbital period. Between 1932 and 1982 AR Lac appears to have undergone several abrupt period changes, one almost as much as 3^s (Wood, 1946; Chambliss, 1976), another of about 20^m (Nha et al., 1982).

(2) Period changes are correlated with the migration of the photometric distortion wave. For AR Lac, period increases have occurred at epochs when the orbital phase of the minimum of the distortion wave was 0.75; decreases, when it was 0.25 (Chambliss, Hall, and Richardson, 1975).

Other observed characteristics of AR Lac are:

1. Photometric Characteristics:
   (a) magnitudes (Chambliss, 1976):
      (1) apparent magnitudes:
         m_V primary = 6.75
         m_V secondary = 6.41
         m_V system max = 6.09
      (2) absolute magnitudes:
         M_V primary = 4.01
         M_V secondary = 3.64
         M_V system = 3.06

Table 1 - continued

(b) coefficient of limb darkening:
  (1) 0.8 from spectral classes (Wood, 1946)
  (2) secondary has very high value (Kron, 1947)
  (3) 0.7-0.8 for primary: from Wood's (1946) data (Kopal and Shapley, 1952)
  (4) secondary high: 1.0 in U; primary low: 0.6 in U (Chambliss, 1976)

(c) secondary more uniformly bright than primary (Wood, 1946; Chambliss, 1976)

(d) nearly central total primary eclipse, annular secondary eclipse (Schneller and Plaut, 1932)

(e) duration of totality = $2^h10^m \pm 15^m$ (Hall, Richardson, and Chambliss, 1976)

(f) variable skewness of secondary minimum (Kron, 1947)

(g) ellipticity and reflectivity effects prominent (Kron, 1947)

(h) depressions preceding first contact and following fourth contact of primary eclipse:
  (1) observed (Kron, 1947)
  (2) 0.05 mag (Catalano, 1973, 1975)
  (3) flanking primary eclipse (Naftilan and Drake, 1977)

(i) variable amplitude of the quasi-sinusoidal wave-like distortion:
  (1) variable throughout cycle, peak at phase 0.6293 in V,B (Babaev, 1974d)
  (2) probably variable, ranging from 0.04 mag to 0.1 mag in blue (Hall, Richardson, and Chambliss, 1976)
  (3) large 0.1-mag amplitude in 1978-1979 after decades of erratic fluctuations (Hall, 1980)
  (4) very low amplitude in 1979 (less than 0.01 mag) (Caton, 1981)

(j) smoothly varying rate of migration of the quasi-sinusoidal wave-like distortion:
  (1) varied smoothly from 1 cycle/50-60 yrs to 1 cycle/10-15 yrs during a 40-yr time period (Hall, Richardson, and Chambliss, 1976)
  (2) rate increased to 0.4 phase units during 1978-1979 (Hall, 1980)
  (3) phase of distortion wave approximately 0.9 in 1979 (Caton, 1981)

(k) smoothly decreasing period of migration of the photometric distortion wave from 1900-1980 = 45-15 yrs (Chambliss, Hall, and Richardson, 1975)

2. Spectroscopic Characteristics:

a. General
  (1) the lines of the primary are sharper than those of the secondary (Harper, 1933; Sanford, 1951; Struve, 1952; Naftilan and Drake, 1977)

Table 1 - continued

(2) absorption lines of primary deeper than those of secondary except from phase $0^d.289-0^d.637$ (Sanford, 1951)
(3) absorption lines of primary strongest when primary receding fastest, weakest when primary approaching fastest (Sanford, 1951)
(4) flat shallow absorption profiles of the secondary (observed in the lines of Ce) characterize the intervals preceding and following primary minimum (Sanford, 1951)
(5) variable changes in line profiles on the ascending and descending branches of the radial velocity curve of the secondary (Struve, 1952)
(6) on the ascending branch of the secondary's radial velocity curve its strong absorption lines (such as Fe I 4045) are strikingly narrow (Struve, 1952)
(7) when the secondary's lines are narrow, it is conspicuous only in the stronger lines (like Fe I 4045), even for lines in the same multiplet (Struve, 1952)
(8) when the secondary's absorption lines are narrow, the corresponding emission lines remain broad (Struve, 1952)
(9) Na I D lines of the secondary show the same structure as other strong lines in the blue; their overall strength is normal for stars of this spectral class, rotation accounted for (Naftilan and Drake, 1977)
(10) equivalent width of Ca II lines variable throughout cycle, pronounced Ca II absorption maximum at phase 0.6489 (Babaev, 1974c)
(11) the absorption lines of the Ca II triplet in the infrared are weak (Hiltner, 1947)
(12) no evidence of Li I 6708 (Naftilan and Drake, 1977; Young and Koniges, 1977)
(13) metal abundances:
  (a) both components underabundant (Miner, 1966)
  (b) primary has solar abundances, secondary moderately underabundant (Naftilan and Drake, 1977; Young and Koniges, 1977)
(14) polarization:
  (a) none detected (Struve, 1948)
  (b) no evidence for circular polarization at radio wavelengths (Owen and Spangler, 1977)
  (c) polarization in V band constant, same as that of interstellar medium (Pfeiffer and Koch, 1977)

Table 1 - continued

(15) no spectral evidence for a third body ever found (Hall, Richardson, and Chambliss, 1976)

b. Emission

(1) all emission lines of the secondary are much stronger than those of the primary:
  (a) ratio of 5:1 for the Ca II emission lines (Joy and Wilson, 1949)
  (b) holds for all lines examined (Naftilan and Drake, 1977)

(2) the Ca II emission lines are present within as well as outside eclipse:
  (a) observed from his own plates (Sanford, 1951)
  (b) from Wyse's 1934 plates: H and K bright at primary minimum totality (Sanford, 1951)

(3) the radial velocity of the H and K emission is 6.4 km/sec less than the radial velocity of all absorption lines in each component (Sanford, 1951)

(4) the equivalent width of the Ca II emission is variable with phase:
  (a) the ratio of the primary's to the secondary's emission increases from phase 0.0-0.5 and decreases from 0.5-1.0 (Sanford, 1951)
  (b) variability observed on Wyse's plates (Kron, 1952)
  (c) basically random, no correlation with phase (Weiler, 1975, 1978)

(5) possible short-term variation of Ca II emission intensity:
  weak self-reversal of K line not seen on all plates; sharp red-displaced absorption seen on one plate; plates from phases 0.983 - 0.003 (Naftilan and Drake, 1977)

(6) no Na I D-line emission has been detected (Young and Koniges, 1977)

(7) emission features in hydrogen lines:
  (a) H-alpha: during primary eclipse and at phase 0.30 there are a possible central emission feature and two weak emission features on both sides of line center and symmetric about line center in and out of eclipse (Naftilan and Drake, 1977); line intensity variable (Weiler, 1975, 1978)
  (b) H-beta: emission during totality (Naftilan, 1975)
  (c) H-gamma and H-delta: during primary eclipse two emission features on each

Table 1 - continued

side of line center (Naftilan and Drake, 1977)

(8) Fe I emission is variable with phase: it is weaker from phase 0.0-0.5 and stronger from phase 0.5-1.0, has a minimum at phase 0.25 and a maximum at phase 0.76 (Sanford, 1951)

(9) soft x-rays detected (Walter, 1978)

(10) variable radio emission:

(a) observed (Hjellming and Blankenship, 1973)

(b) variable on a scale of greater than a few hours; during secondary eclipse there was a small increase in flux density; at phase 0.98 there was a depression of about 25% superposed on a longer-time-scale rise (Owen and Spangler, 1977)

(c) radio flare (Feldman, 1978)

3. Correlation of Optical and Radio Behavior

(a) no correlation of optical variations and radio outbursts (Chambliss, 1976)

(b) no strong eclipse-like radio feature occurred during optical eclipses (Owen and Spangler, 1977)

4. Physical Characteristics

(a) radii (Chambliss, 1976):

(1) $R_{primary} = 1.54\ R_{\odot}$

(2) $R_{secondary} = 2.81\ R_{\odot}$

(b) masses (Popper, 1967):

(1) $M_{primary} = 1.32 \pm 0.06\ M_{\odot}$

(2) $M_{secondary} = 1.31 \pm 0.07\ M_{\odot}$

(c) system is detached (Kopal, 1958)

(d) temperatures:

(1) 5600K for G2 IV, 4700K for K0 IV (Chambliss, 1976)

(2) very nearly the same for U, B, V light curves (Chambliss, 1976)

(e) microturbulence velocity:
secondary has an anomalously high value for a subgiant (10 km/s); primary is not far behind (8 km/s) (Naftilan and Drake, 1977).

5. Orbital Characteristics

(a) $i = 86°$ (Rugemer, 1931; Schneller and Plaut, 1932)

(b) $P = 1^{d}.983$ (Rugemer, 1931; Schneller and Plaut, 1932)

(c) $a = 8.92\ R_{\odot} = 0.0429$ AU (Chambliss, 1976)

(d) d = 40 pc (Chambliss, 1976)

(e) e = 0 (Sanford, 1951; Chambliss, 1976)

Table 2
RS CVn BINARY STAR SYSTEMS

Name[a]	V_{max}[a] (mag)	Orbital Period[a] (days)	Spectral Type[a] (hot + cool)	H and K Emission[b,k]	Distortion Wave Amplitude[a] (mag)
UX Ari	6.5	6.438	G5 V + K0 IV	S[d]	0.03-0.10
CQ Aur	9.0	10.621	G0 + ?	P(S?[e])	0.06-0.12
SS Boo	10.3	7.606	G5 V + G8 V	S	0.05-0.19
SS Cam	10.0	4.824	F5 V + G1 V	S	0.11
AD Cap	9.8	6.118	G5 + G5	P+S	??
RU Cnc	10.1	10.173	F9 V + G9 V	S	0.02-0.09
UX Com	10.0	3.642	G5-9	S[e]	0.10
RS CVn	8.4	4.498	F4 V-IV + K0 IV	S	0.05-0.20
RT CrB	10.2	5.117	G0	S[d]	0.04
WW Dra	8.8	4.630	G2 IV + K0 IV	S	0.06
Z Her	7.3	3.993	F4 V-IV + K0 IV	S	0.03
AW Her	9.7	8.801	G2 IV + K2 IV	S	??
MM Her	9.5	7.960	G8 IV	S	0.06-0.12
PW Her	9.9	2.881	G0	S	0.12
GK Hya	9.4	3.587	G4	S[d]	?
AR Lac	6.9	1.983	G2 IV + K0 IV	P+S	0.04
RT Lac	9.0	5.074	G9 IV + K1 IV	P+S	0.01-0.17
RV Lib	9.0	10.722	G5 + K5	P+S[e]	0.06
VV Mon	9.4	6.051	G0	S	0.01-0.09
LX Per	8.1	8.038	G0 V + K0 IV	S	0.01-0.05
SZ Psc	7.3	3.966	F8 V + K1 V-IV	S	0.02-0.15
TY Pyx	6.9	3.199	G5 + G5	P+S	0.04
V711 Tau	5.9	2.8	G5	P+S[g]	0.07-0.21
RW UMa	10.2	7.328	F9 V + K1 IV	S	0.11
RS UMi	10.1	6.2	F8	S[e]	??
HR 5110	5.0	2.613	F2 IV + K IV	S[c]	0.00
HD 5303	7.8	1.840	G2 V + F0	P[h]	0.3
HD 175742	8.4[i]	2.879	K0 V + K5 V-M2 V	?[f]	0.079
HD 178450	8.1[j]	2.185	G6 V	?[f]	0.033
HD 224085	7.6	6.724	K2-3 IV-V	?[f]	??

? Detected, but not yet measured
?? Unknown
a Hall (1981), except where otherwise indicated
b Oliver (1974), except where otherwise indicated
c Conti (1967)
d Hall (1976)
e Popper (1976)
f Joy and Wilson (1949)
g Weiler (1976)
h Hearnshaw and Oliver (1977)
i Henry (1981a)
j Henry (1981b)
k P = emission in hotter star (primary);
S = emission in cooler star (secondary);
P+S = emission in both components

SECTION II
INSTRUMENTATION AND OBSERVATIONS

Instrumentation

Telescope

The telescope which was used in this investigation is the Tinsley Newtonian-Cassegrain 76-cm instrument at Rosemary Hill Observatory. The telescope was operated in the f/16 Cassegrain mode. (See Wheeler, 1973, for the equations used to calculate the parameters cited below.)

Spectrograph

The spectrograph which was used is a Boller and Chivens Model 26767 f/13.5 Cassegrain spectrograph equipped with a corrector lens for the conversion of the incoming telescope beam from f/16 to f/13.5, thereby providing a reciprocal scale of 20"/mm in the slit plane. The focal ratio of the spectrograph camera is f/3. The aluminized glass slit plate has fixed slit widths of 28, 40, 56, 80, 112, and 160 microns. The 56-micron slit corresponds to an angular image size of 1" at the slit plane. The decker plate has fixed slit lengths (deckers) of 1.5, 3, 6, 13, and 25 mm. Two holes of 0.5 and 0.75 mm were drilled into the decker plate to be used as shorter slit lengths to allow shorter exposure times.

The spectrograph is equipped with a variable-focus collimator and an adjustable grating tilt. (The spectrograph is worked at negative grating angles.) There are two interchangeable 64mm X 64mm gratings. Grating I, ruled at 150 lines/mm, produces a linear reciprocal dispersion of 128 A/mm at 3933 A in the third order. Grating II, ruled at 300 lines/mm, produces a linear reciprocal dispersion of 60 A/mm at 3933 A in the third order. Both gratings are blazed at a wavelength of 1.25 microns, and the wavelength of maximum energy in the third order is 3776 A. The resolution limit of grating I is 0.14 A, and that of grating II is 0.068 A, both at 3933 A in the third order.

The comparison source is a helium-argon glow lamp. Positions are provided for the insertion of filters into the comparison source beam as well as into the incoming stellar beam.

The manufacturer-supplied slit-viewing eyepiece was inadequate for observation of stars fainter than sixth magnitude. (The small aperture of the exit pupil allowed only about two-thirds of the beam of starlight reflected from the slit edges to emerge from the system.) This eyepiece was replaced with an improved design (devised by Hoffman and Oliver) featuring an enlarged exit pupil and increased magnification (15X rather than the previous 10X) so that the slits and the deckers could be viewed in greater detail.

An image tube was used for some spectra in attempts to (1) reduce exposure times and (2) obtain spectra of the sodium D lines in the second-order yellow.

An exposure meter (designed by Oliver) which employed an end-window S20 EMI 9558A photomultiplier tube was constructed. Although excellent for bright stars or a dark sky, the meter was unable to discriminate between a faint star and a bright sky background, thereby grossly undercounting the stellar photons and rendering erroneously lengthy exposure times. It was abandoned in favor of directly timed exposures until a more suitable tube could be obtained. (See Section VI.)

Plates

The spectroscopic plates used were backed plates of emulsion type IIa-O, which were cut to 2-in x 2-in squares from larger plates and then hypersensitized (both done by the author). The hypersensitization/storage procedure for the plates (Smith, 1975) consisted of (1) evacuation of the plate-filled thick-walled aluminum plate-storage box, (2) back-filling with anhydrous hydrogen, (3) storage of the plates in the hydrogen for 2^h, (4) flushing with anhydrous nitrogen and (5) subsequent refrigerated storage of the plates in the nitrogen at greater than 1 atm of pressure. In addition, the plate box was sealed within a deflated zip-lock bag containing a canister of silica gel desiccant, the addition of the desiccant being an innovation suggested by the author.

The IIa-O emulsion has a linear resolution limit of 16 microns. At the dispersion of grating I at 3933 A in the third order, the wavelength resolution limit of this emulsion is 2.3 A. The corresponding wavelength resolution limit for this emulsion in combination with grating II is 1.2 A.

Sensitometer

The Florida-Smithsonian Plate Sensitometer was used to record spots of standard emulsion density on a sample plate from each hypersensitization batch. Designed in 1969 by Smith (1977a), this instrument is a variable-illumination-constant-exposure-time tube sensitometer, which produces an intensity scale of graduated emulsion densities (Jones, 1931, 1934). In order to minimize errors due to reciprocity failure, (1) the sensitometry spots were exposed for times as close as possible to those of the stellar exposures, and (2) the sensitometry plates were developed by the same procedure as that for the stellar plates (Wright, 1962).

Densitometers

A Model 520-A Photovolt transmission densitometer was used to measure the densities of the spots on the standard sensitometry plates and the densities of the unexposed areas on the stellar plates.

A Joyce, Loebl and Co. Ltd. Model MK III CS double-beam recording (scanning) microdensitometer with a Honeywell strip-chart recorder was used to obtain tracings of the lines on the spectrograms and of the spots on the

sensitometry plates. The controlled adjustments on the recording (scanning) microdensitometer are the gain settings for the level of the sample light beam relative to the standard reference light beam, the heights and widths of the upper and lower slits, the focusing of the image of the lower slit onto the plane of the upper slit, and the focusing of the image of the plate onto the plane of the upper slit. Inadequacies in the microdensitometer system necessitated its modification by Oliver, Parise, and Hoffman: (1) The non-functioning logarithmic amplifier was eliminated from the circuitry, thereby converting the strip-chart deflection readout from emulsion-density units to units which are a function of emulsion-transmission.(2) The scanning speed of the microdensitometer and the chart speed of the chart recorder were reduced in order to achieve greater spectral resolution on the chart and to minimize distortion of the line profiles. No attempt was made to determine the instrumental profile for the reason that broad lines (like H, Cr, and Ca II H and K) are virtually free of instrumental effects (Wright, 1962). (3) The vertical range ("transmission" scale) of the chart recorder was extended by the incorporation of a zero-level-maximum-level potentiometer, which enabled the entire width of the chart paper to be used. This modification also effected enhancement of the visibility of small changes in transmission level.

Calculator

A Hewlett-Packard Model 9810A calculator was programmed to perform a linear regression to determine the functional relationship between "transmission" level and intensity at each wavelength.

Observing Program

Between 1971 and 1978, 153 spectra of single stars, stellar systems, and planets were obtained. This series of spectrographic observations marked the inception of astronomical spectroscopy at the University of Florida.

The spectra of single stars were used to establish

(1) a relationship between apparent visual magnitude and exposure time as a function of spectral type and varying sky conditions, and

(2) an atlas of spectra of MK standard stars (Johnson and Morgan, 1953) for the purpose of spectral classification.

The primary portion of the program consisted of the observation of the RS Canum Venaticorum binary star systems.

In order to determine which of the RS CVn systems are observable and analyzable with the available optical systems, selection criteria were established according to the capabilities of the telescope-spectrograph system, the scanning microdensitometer system, and the stars themselves.

Two exposure requirements imposed by the telescope-spectrograph system and the physical parameters of the

star systems provided the basis for selection of observable stars:

(1) It was necessary to obtain the shortest possible exposure time in order to achieve adequate time resolution to allow observation of detailed changes in the H and K emission as a function of phase, particularly at the phases at or near the relatively short (about 2^h) eclipses.

(2) The spectra had to be overexposed in order to reveal the emission reversal. This requirement resulted in exposure times approximately 25% greater than those necessary to produce a density of 0.6 in the local continuum. Additional exposure time was needed to compensate for haze, enlarged discs, and large air mass.

These constraints restricted the observations to systems of average visual magnitude brighter than 7.5. Imposing this condition narrowed to only six the field of RS CVn systems which could feasibly be observed. The six systems which fulfill the observational criteria are UX Arietis, HR 1099 (V711 Tauri), TY Pyxidis, Z Herculis, RZ Eridani, and AR Lacertae. (RS CVn itself, however, was observed on a few occasions for purposes of comparison.)

Although TY Pyx is one of the brightest of the RS CVn systems, its extremely large zenith angle (58° minimum) at this latitude (30° N) forced observation through a large air mass, which rendered the necessary exposure time too long to

allow sufficient time resolution. Seasonal burning of undergrowth by nearby landowners required an additional increase in exposure time (if the star could be seen at all). The weakness of the emission in TY Pyx further compounded the problem to the extent that the system was eliminated from the observing program.

RZ Eri was subsequently deleted from the membership of the RS CVn group for failure to satisfy the period requirement (1^d-14^d) established by Hall (1976).

The four remaining systems which satisfy the magnitude requirements are the stars which were regularly observed in the program.

An additional system, HR 5110, was observed because it was suspected of being an RS CVn system. No strong H and K emission was observed; therefore it was deleted from the program. Hall et al. (1978), however, list it as an RS CVn system.

The inability of the scanning microdensitometer to analyze plates of poor quality dictated the remaining criterion for selection among the plates of systems which fulfill the observational criteria.

Of the 67 plates of RS CVn systems, 3 were made using the image tube in conjunction with the spectrograph in attempts to (1) enhance time resolution by reducing exposure times and (2) record data on the sodium D lines in the second order yellow. The image tube, however, was abandoned because it yielded plates of very poor spectral resolution

and very high fog levels. These effects were encountered primarily because of arcing between the plate and the face of the image tube due to the extremely high humidity. The problem persisted despite the installation of a heating ring to dissipate moisture.

Of the remaining 64 plates of RS CVn stars, 51 were of sufficient quality to be analyzed. The 13 which could not be analyzed were rendered unusable for one or more of the following reasons:

(1) high fog level produced by long exposure to high humidity,

(2) lines too thin due to inadequate exposure time because of haze, clouds, etc., and/or

(3) lines insufficiently widened by use of short deckers in attempts to reduce exposure times (short deckers rendered the spectra so narrow that too little information was recorded for analysis with the available equipment).

The usable plates of the stars fulfilling the observation criteria tallied 11 for UX Ari, 10 for HR 1099, 4 for Z Her, and 19 for AR Lac. (See Section VI for plans for analysis of the first three systems listed.) The other 7 usable plates were of RS CVn stars which did not fulfill the observation criteria.

AR Lac was the system chosen for analysis because for this system the amount of data obtained was greater than for any of the others and because the need for additional data

analysis was greater than for all of the others. Also, the spectrograms of the other three aforementioned systems did not offer enough coverage of their entire cycles to allow any definitive conclusion to be drawn regarding the behavior of their Ca II emission. The 19 spectrograms of AR Lac span the entire orbital cycle of the system, an achievement which required more than one epoch of observation. AR Lac's nearly integral period ($1^{d}.983$) produces a rate of phase change of only 0.004 phase unit per day (placing the system at approximately the same phase at the same time on successive nights), a circumstance which necessitates an extended program of observation to obtain spectra at all phases.

All of the spectra of AR Lac were recorded on IIa-O spectrographic plates at a linear reciprocal dispersion of 128 A/mm with grating I (150 lines/mm). A slit width of 80 microns was used because it (1) corresponds almost exactly to the diameter of the usual seeing disc (about $1''.5$) at Rosemary Hill Observatory and (2) provides the minimum resolution required to observe the desired detail in the spectra. The spectra were widened by trailing along a slit length (decker) of 1.5 mm. Exposure times ranged from 40^{m} on clear nights of good seeing to 90^{m} on hazy nights or nights of poor seeing.

SECTION III
DATA REDUCTION

Procedure and Theory

The following procedure was used to obtain and reduce the data. Any theory necessary to the data reduction has been incorporated into the discussion.

There does exist a problem of disparate nomenclature among the five disciplines--astrophysics, optics, spectroscopy, photography, and photometry--which enter into this investigation. Each field has its own definition for items such as intensity and brightness, and a term widely used in one field may be unacceptable in another. Clarifications are parenthetically included where two conflicting nomenclatural systems are simultaneously encountered. If, however, the discussion is confined to a single discipline or to non-conflicting disciplines, no alternative terms are listed; but archaic terminology has been replaced, where necessary, by the proper modern term in the parlance of that field.

Plate-Tracing

Three tracings of each stellar spectrogram were obtained using the recording (scanning) microdensitometer. The plates were scanned from 3889 A to 4026 A. On each spectrum scan, tracings of the sensitometry plates were recorded across the full range of the chart paper at the

same gain setting, slit width, and slit height as was the spectrogram tracing.

Minimum deflection on the chart paper, indicating maximum emission intensity recorded by the emulsion at a given wavelength (maximum flux density received at the earth at a given wavelength), was scaled to correspond to an emulsion transmission of zero by adjustment of the chart-recorder zero-level potentiometer while the sample beam was passed through the densest (blackest) part of the continuum in the vicinity of the H and K lines. The densest part of the local continuum at H and K was determined by microscopic examination to be at 4026 A.

Maximum deflection on the chart paper, indicating minimum emission intensity recorded by the emulsion at a given wavelength (minimum flux density received at the earth at that wavelength), was scaled to correspond to an emulsion transmission of 100% by equalization of the sample- and reference-beam levels and adjustment of the chart recorder maximum-level potentiometer while the sample beam was passed through the plate fog (the "clear" area on the plate).

It was determined experimentally that a slit width setting of 30 is optimum for obtaining the maximum amount of light possible while still preserving the resolution of detail in the line tracing. The focus of the plate image onto the upper slit is critical to resolution.

As was stated in Densitometers, Section II, the instrumental profile was not measured, a step which would be

necessary in order to determine the true line profile. This step was unnecessary not only for the (previously stated) reason that there is virtually no distortion in broad lines (Wright, 1962) but also for the reason that the calculation of equivalent width circumvents the problem because equivalent width is independent of instrumental profile (Aller, 1951; Stromgren, 1951; Thackeray, 1961).

In order to reduce noise introduced by the recording microdensitometer and the chart recorder, point-by-point averages of the three tracings of each stellar spectrogram and its accompanying sensitometry spots were graphically computed. The chart paper which must be used on the chart recorder has a grid size too large to render a faithful reproduction of the precision attained by the tracing system and the plates; therefore the averaged tracings were transferred point-by-point to 0.1-inch chart paper for greater precision of deflection-reading. The resulting tracings displayed deflection (ordinate) as a function of wavelength interval (abscissa).

In order to convert the wavelength intervals to Angstroms the wavelength scale factor for the chart paper was calculated (1.18 ± 0.06 A/div) and applied.

The recorded deflection at each point in a line tracing is a measure of the emulsion transmission (T), where T is defined as the ratio of the measured photographic intensity at a given wavelength to a standard photographic intensity. In this case the standard was chosen to be the continuum at

4026 A, so that $T = I/I_{CONT}$. The electronics of the scanning microdensitometer, however, could not be calibrated so that deflection would be a direct readout of either emulsion transmission or emulsion density ($D = \log 1/T$). Further conversion was therefore required.

Conversion of Deflections to Relative Intensities

Because the relationship between deflection and intensity was unknown, it was necessary to determine that correspondence through the application of the characteristic curve for the emulsion. The deflections were converted to relative intensity units by the following procedure.

Density-deflection relations: D(d)

The transmission densitometer was used to measure the densities of the sensitometry spots on each sensitometry plate and the densities of the clear areas on the stellar plates. The correspondence of each spot-density to its measured deflection on the scanning microdensitometer tracing for each stellar plate established a relationship between density and deflection at the gain setting used for each tracing. A graph of deflection (abscissa) versus density (ordinate) was plotted for each stellar plate.

Because the transmission densitometer is designed to measure diffuse density and the scanning microdensitometer is designed to measure specular density, a question might arise regarding the possibility of encountering errors due to the procedure employed herein. A comparison of densities measured by the two instruments might yield a difference as

great as 50%, which would be equivalently expressed as a ratio of 2:1 by the Callier factor, the ratio of specular to diffuse density (Neblette, 1970). In the present calibration, however, there were no such comparisons made. Instead, emulsion densities measured with the transmission densitometer were correlated with the deflections measured by the scanning microdensitometer in order to establish a scale of relative densities for the spectra traced by the latter instrument. This procedure was necessitated by the lack of an available density calibration for the scanning microdensitometer. Because this procedure did not involve a comparison of densities measured by the two different methods, there was no additional error other than the usual amount incurred by reading data from a strip chart.

Through the use of sensitometry spots to calibrate a stellar spectrum (Wright, 1962), an unknown, but probably small, error was encountered.

Both of the errors cited above are included in the discussion in the segment entitled Determination of Error in the equivalent width of the K-line emission.

Characteristic curves (D-log E curves): D(log E) and D(E)

By use of the sensitometer correlation established by Smith (1977b) between sensitometry spot number and logarithm of relative exposure, a characteristic curve, D(log E), was plotted for each stellar plate. Spot number, representing the logarithm of relative exposure (abscissa), was plotted versus density (ordinate) for each stellar plate. The

characteristic curves were transferred data-point-by-data-point to semilog paper in order to facilitate the reading of the density-relative exposure coordinates. Relative exposure (abscissa) was plotted on the logarithmic scale; and density (ordinate), on the linear scale, in order to obtain the functional relation D(E).

Relative exposure-deflection relations and relative intensity-deflection relations: E(d) and I(d)

Correlation of relative exposures with deflections through the use of the data points on the density-deflection graphs and on the density-relative exposure curves allowed the construction of a relative exposure-deflection curve, E(d), for each stellar plate. Plotted on semilog paper, relative exposure (ordinate, on the logarithmic scale) was expressed as a function of deflection (abscissa, on the linear scale).

Because these graphs appeared to be very nearly linear, a Hewlett-Packard 9810A linear regression program was used to derive empirically an equation, E(d), for relative exposure as a function of deflection for each stellar plate. (The linearity correlation for each resulting equation was greater than 0.99.) This step greatly facilitated the process of determining the relative exposure resulting from a given deflection recorded on the stellar plate tracings. Without an available equation the relative exposure-deflection graphs would have had to have been used to read the relative exposure for each deflection-data-point on each

stellar plate. This procedure would have entailed hundreds of individual correlations and would have taken considerably longer to complete.

Upon establishment of the relative exposure-deflection function, E(d), for each plate, the relative intensity-deflection function, I(d), for each plate was immediately known because relative intensity is directly proportional to relative exposure for a plate of given exposure time.

Relative plate speeds

The relative plate speed of two plates is the ratio of the inverses of their relative exposures at a given density. In order to compare on the same scale the relative intensities of plates of different relative speeds, the stellar plates would be standardized relative to the speed of an arbitrarily selected sensitometry plate by simply dividing the speed of each plate by the speed of the sensitometry plate. In this investigation, however, only ratios of relative photographic intensities of a given plate were used; consequently the determination of relative speeds was not necessary.

Photographic normalization of relative intensities

At each 0.1-inch grid-line of the wavelength axis of each stellar plate tracing, deflection (in number of 0.1-inch intervals along the intensity axis) was read. Substitution of each deflection into the Hewlett-Packard 9810A relative intensity-deflection equation for that stellar plate and subsequent division of the calculated

relative intensity at each wavelength by the relative intensity of the local continuum for each stellar plate resulted in a printout of tabulated relative intensities photographically normalized to the intensity of the local continuum for each plate.

Calculation of Equivalent Widths

The equivalent width of the K emission was determined by the following procedure.

Actual (absorption-plus-emission) line profiles

In keeping with standard spectroscopic methods (Keenan and Morgan, 1951) the line profile for the K line was constructed for each stellar plate by plotting the tabulated relative intensities normalized to the intensity of the local continuum (ordinate) as a function of wavelength (abscissa) on 0.1-inch graph paper. These line profiles, constructed from the original data, are superpositions of the K absorption and the K emission for both stellar components of the system at the orbital phase of the spectrogram. The linear reciprocal dispersion of 128 A/mm is too low by a factor of two to resolve the K-line components of the individual stars at any phase. (See Figure 1.)

At every phase the scaled line profile exhibits a small, narrow emission core of variable strength and position superposed on deep (except at primary minimum), broad absorption about 30 A wide at the continuum level. (See primary minimum, below.) Unidentified narrow

absorption lines flank and are blended with the major absorption core of the K line. (See Figure 1.) The profiles in this investigation are virtually identical to those observed at corresponding phases by Babaev (1974a).

The emission core broadening has variously been attributed to turbulence in an optically thin layer (Wilson and Bappu, 1957) and abundance in an optically thick layer (Goldberg, 1964; Linsky and Avrett, 1970).

The absorption core is broadened by thermal motions, microturbulence (Naftilan and Drake, 1977) and turbulence (Abell, 1982), and rotation (Sanford, 1951). The microturbulent and turbulent broadening is evident in the anomalously broad bell-shaped Gaussian (Doppler) core, whose width far exceeds that of normal thermal broadening. The rotational effects add to the core profile, rendering the core broader and shallower. The characteristic broad, shallow shape of a rotationally broadened line is most apparent at phases during primary eclipse, when only the large, rapidly rotating K star is visible. (See Sanford, 1951.)

The true extent of any absorption wings is difficult to discern in the profiles in this investigation and in general because of the lack of a true continuum level in this wavelength region so dense in spectral lines (Wright, 1962). Linsky and Avrett (1970) determined that for wavelengths shorter than 4000 A in the sun there is no true continuum level except for an interval 0.08 A wide at

3999.89 A. Comparisons can be made to the profiles of other observers, however. Line profiles published by Struve (1948) exhibited broad absorption wings in the H and K lines of AR Lac. Joy and Wilson spoke of the "great absorption wings" (Joy and Wilson, 1949, p. 231) of the H and K lines in late-type stars, and Weiler (1978) mentioned the overlap of the wings of the H and K lines of RS CVn stars. Other observers mentioned only that the H and K lines are characterized by broad absorption and sharp emission. The wings could be generated by rotational broadening alone or by rotation plus abundance effects (collision, radiation, and/or pressure broadening). These observers did not attribute the wings to any particular process, but those in Struve's (1948) paper match fairly well with a superposed Lorentzian curve, the shape of which would be produced by abundance broadening.

Emissionless profiles

By the following procedure an emissionless profile for the K line of the system was constructed empirically for the phase of each stellar plate.

The emissionless profile for the K star. Because the primary eclipse of AR Lac is total (Scheller and Plaut, 1932), the actual (absorption-plus-emission) profile for the K star alone could be determined by taking the graphical mean of all the profiles during totality. (Only one spectrogram was obtained at this phase.) The emissionless profile for the K star alone was determined by visually

estimating by the following procedure what the appearance of this line profile would be without the emission peaks. (See Figure 2.)

The fact that the profile at totality was quite evidently degraded considerably by emission and broadened and shallowed by rotation were great hindrances; however, by modeling the emissionless profile after the general characteristics of the K line and after the general appearance of the K line in the sun and in other late-type stars, a reasonable picture, internally consistent with all the data, was developed.

The great depth selected for the constructed emissionless profile is justified by the fact that the K line is a resonance line. The line centers of such lines are characterized by an extremely low residual intensity, which can be attributed to the apparent characteristic tendency for resonance lines to be formed by the mechanism of scattering rather than absorption. There are two scattering processes: coherent and non-coherent.

In the coherent scattering process the probability of a quantum's reaching the stellar surface from great depths is very low because it is absorbed and re-emitted in no preferred direction; consequently the line center is virtually black (less than 1% of the continuum: Linsky and Avrett, 1970). In actuality no line center is truly black, though; for there is <u>some</u> probability of a quantum's emergence.

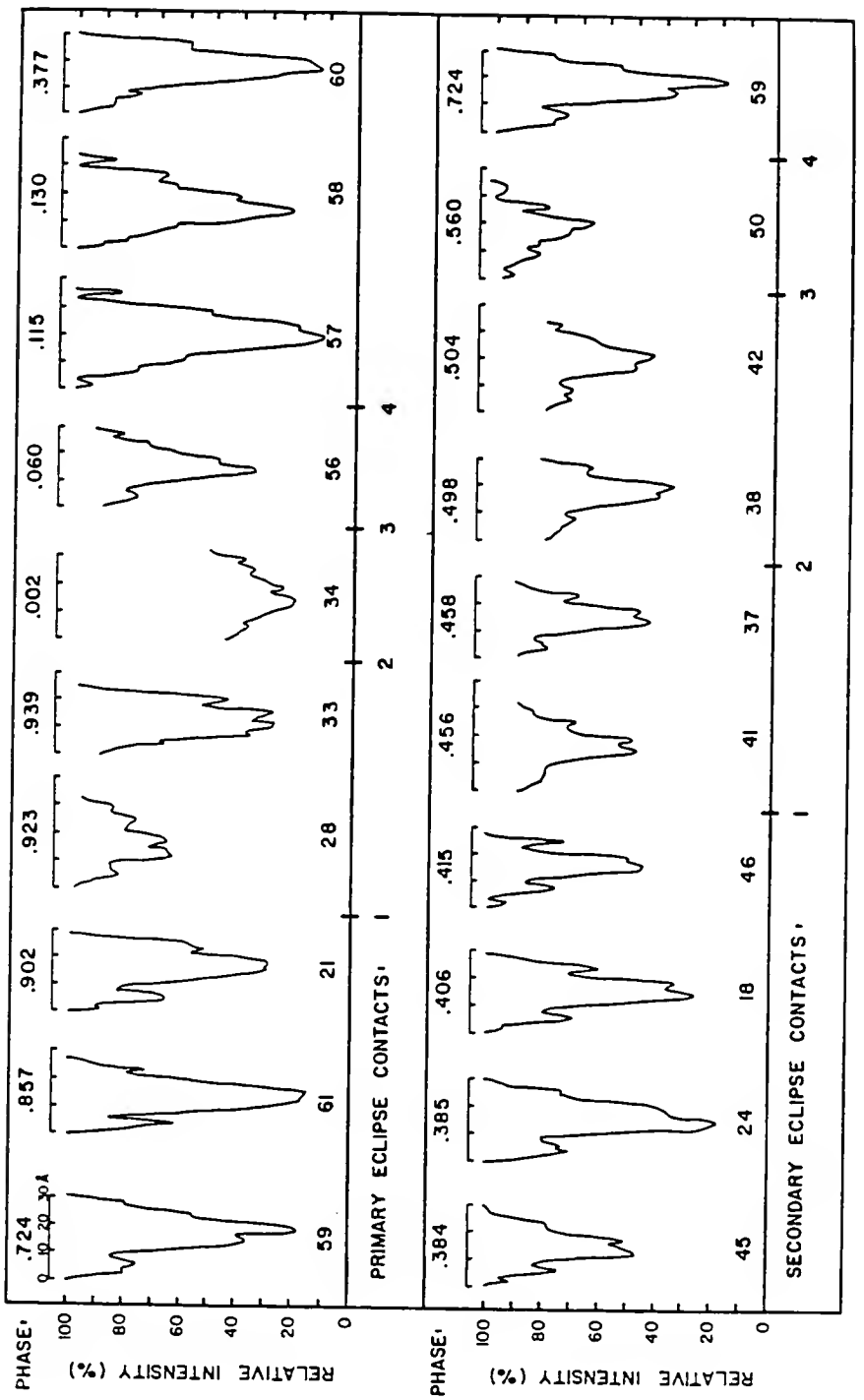
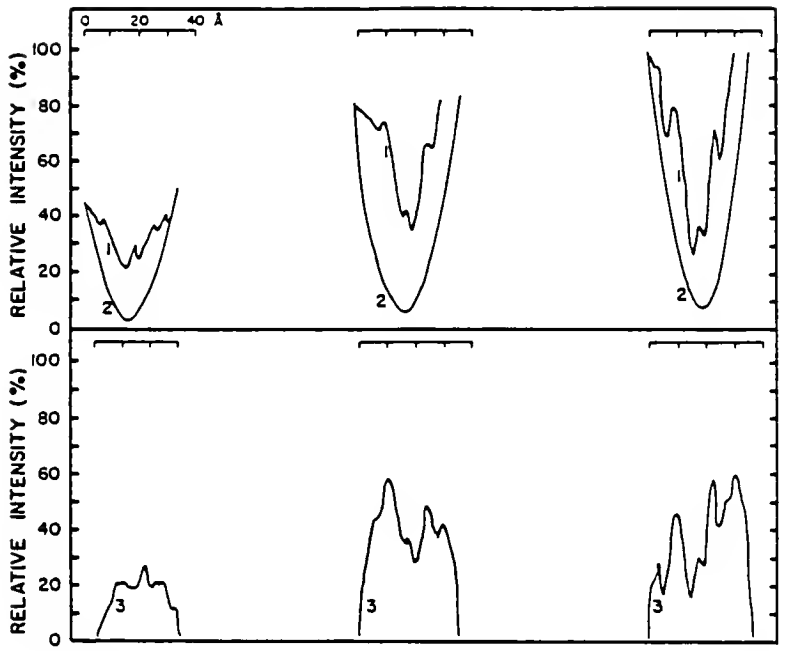


Figure 1
PROFILES OF THE Ca II K LINE IN AR Lac

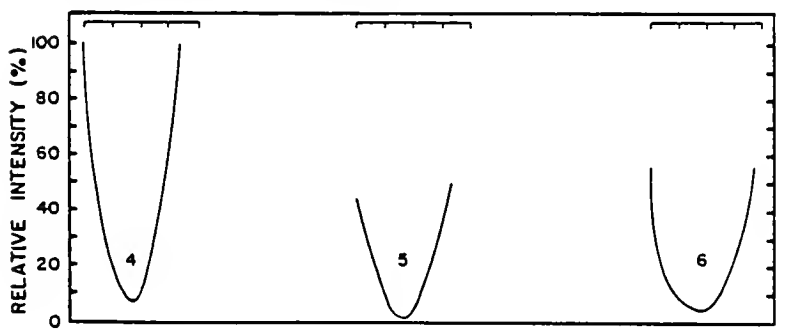


a. Primary Eclipse Profiles (K star) (plate 34)

b. Secondary Eclipse Profiles (G star plus annulus of K star) (plate 38)

c. Extra-eclipse Profiles (G star plus K star) (plate 18)

1 scaled profile (absorption plus emission)
2 empirically constructed theoretical emissionless profile (absorption)
3 emission profile (1 minus 2)



d. Construction of the Absorption Profile for the G Star

4 same as c2
5 same as a2
6 empirically constructed theoretical emissionless profile for the G star (4 minus 5)

Figure 2
CONSTRUCTION OF EMISSIONLESS PROFILES
FOR THE Ca II K LINE IN AR Lac

For the cores of the H and K lines in the sun, however, and probably in all other stars also, non-coherent scattering is the process which renders the central intensity non-zero (Linsky and Avrett, 1970). Non-coherent scattering arises because lines are not perfectly sharp; therefore a quantum absorbed in one part of the line is not guaranteed to be re-emitted from the same part of the line. This process results in a redistribution of the energy across the line profile, transferring energy from the wings to the core, thereby producing a greater central intensity than does coherent scattering. In the observed solar K-line absorption profile, smooth extrapolation of the sigmoid curve of the Doppler core to the line center yields a central residual intensity of only a few percent (4% at most; i.e., $I/I_{CONT} = 0.04$: Aller, 1963). Theoretical absorption profiles for the solar K line present a similar picture (Aller, 1963).

Modeling the emissionless line profiles after those of the sun constituted an empirical method which produced inexact results; consequently any calculated differences or ratios between the emissionless profiles and the actual profiles could be only relative values. Determination of the absolute values of (rather than the relative changes in) the line profiles would require the precise calculation of a theoretical line profile. This procedure would involve the calculation of a model atmosphere, which would include

(1) the determination of the line absorption coefficient dictated by the chosen model atmosphere and (2) the assumption of a line-forming mechanism (Aller, 1963). There are apparently no completed model atmosphere calculations for the AR Lac system or a similar one.

Other observers (e.g., Weiler, 1978) have constructed emissionless profiles by utilizing the Ca II line shapes observed in spectra of single stars of the same spectral or spectral-luminosity class as the stars in the AR Lac system. Because there is some emission in these single stars, employment of this method did not avoid the problem of deciding the depth of the line empirically, but merely Doppler-narrowed it slightly because single stars of these spectral classes display much less rotational broadening than do stars of the same classes in binaries.

Photometric scaling. Each of the ten spectra obtained at phases outside eclipse exhibits a superposition of the spectra from the entire discs of both stars. As a preliminary step to determining the emissionless profiles for these combination spectra, their actual (absorption-plus-emission) profiles were photometrically scaled on the assumption that the U light level (the ultraviolet light level as measured in the standard UBV photometric system) outside eclipse is constant. This practice is equivalent to assuming that the U light output of each star is (1) isotropic over its surface and (2) invariant with respect to time.

This assumption is not strictly true for AR Lac because there are small irregular variations in the light curve out of eclipse and additional periodic variations due to the photometric wave-like distortion. The small irregular variations amount to only 0.025 mag (Chambliss, 1976), and the amplitude of the distortion wave during the epochs of this investigation (1976-1978) was only 0.04 mag. The combination of these two effects resulted in a total U intensity variation of only 0.3%, which is negligible. The extra-eclipse U light level therefore provides a virtually constant level to be used as a reference standard by which to (1) scale light levels at all phases and (2) make absolute comparisons among data of various observers. All extra-eclipse profiles were therefore photometrically scaled to the same U light level, selected to be equal to the maximum U light level (the extra-eclipse U light level) of the system.

The emissionless profile for both stars in combination. By alignment of the short-wavelength continuum edges of all the extra-eclipse photometrically scaled actual profiles, a composite was constructed to synthesize the appearance of the actual combination spectrum of both stars. Use of a composite rather than a spectrum at a single phase tended to smooth any variations due to possible differences in amounts of emission at different phases and any Doppler shifting in position of emission peaks across the absorption profiles at different phases.

To obtain the emissionless profile for the sum of the K-lines of both stars, a smooth deep envelope was constructed on the composite, which already exhibited a center-line residual intensity of only about 8%. This envelope was employed in the data analysis as the representation of the combination emissionless profile at all phases. (See Figure 2.)

Further photometric scaling. As a preliminary step to determining the emissionless profile for the G star alone, the K star's emissionless profile was photometrically scaled so that it could be graphically subtracted from the combination emissionless profile. On the assumptions that (1) each star's photographically normalized U continuum is equal to that star's fractional contribution to the total extra-eclipse U light of the system and that (2) the intensity at each wavelength in the line profile of each star is proportional to that star's fractional contribution to the total extra-eclipse U light level of the system (see Binnendijk, 1960, pp. 180ff, 264ff), Chambliss' (1976) photometric data were used to scale the K star's extra-eclipse U continuum level to 44% of the total extra-eclipse U continuum level of the system. (The value used for the G star was, then, of course, 56%.)

The emissionless profile for the G star. With the K star's extra-eclipse U continuum level scaled at 0.44 and the extra-eclipse combination continuum level scaled at 1.00, the K star's emissionless profile was centered on the

combination emissionless profile and subtracted from it point by point. The resulting emissionless profile for the G star exhibited an extra-eclipse U continuum level of 0.56 with respect to the total extra-eclipse U continuum level of the system. (See Figure 2.)

Synthesized emissionless profiles. After obtaining an emissionless profile for each star, combination emissionless profiles were synthesized for the phase of each spectrogram by graphically adding the K- and G-star emissionless profiles after they had been (1) photometrically scaled to the proper proportion for that phase and (2) Doppler-shifted relative to each other according to their relative radial velocity at that phase. Basing the emissionless profiles (i.e., the absorption profiles) for all phases on the emissionless profiles for one phase is tantamount to assuming that (1) any changes in the actual (absorption-plus-emission) profiles are caused by variations in emission rather than in absorption or in both--(Weiler (1978) assumed this--and that (2) the absorption profile of each star is the same shape for all phases and for all time (i.e., that the absorption profile is uniform over the surface of the star at all times). The following procedure was employed to generate the syntheses.

The combination emissionless profile for each phase outside eclipse was formed simply by graphically adding the Doppler-shifted emissionless profile of the G star at a given phase (its continuum photometrically scaled to 0.56)

and of the K star at that phase (its continuum photometrically scaled to 0.44). All of the extra-eclipse combination emissionless profiles were therefore scaled to a U continuum level of 1.00.

Synthesis of emissionless profiles for eclipse phases required additional photometric scaling. During phases of partial eclipse of stars with uniform luminances, the fractional U contribution from each star relative to the total U light of the system at that phase is equal to the unocculted fraction of the star's disc area. As previously stated, the U continuum contribution of each star is also this fraction; and the intensity at each wavelength in the absorption line profile is assumed to be proportional to this fraction.

The components of AR Lac, however, are not of uniform luminance. The limb darkening in the K star is high; that for the G star is relatively low (Chambliss, 1976). Chambliss calculated the limb darkening coefficient for each star by determining the values which yielded photometric solutions consistent with his data. By this process he was forced to one extreme with the K star--obtaining 1.0 as its limb darkening coefficient in the U. The U limb darkening coefficient for the G star was calculated to be 0.6. In the present investigation, the value for the K star was assumed to be 0.8 (thereby softening somewhat Chambliss' extreme value), but the value for the G star was placed at the other extreme--it was assumed to be 0.0.

Because the G star was assumed to be of uniform luminance, the disc-fraction rule was applicable during the partial and total phases of primary minimum, when the K star is occulting part or all of the G star, respectively. For example, at one of the partial phases of primary minimum the total U light from the system was 0.89 of the total extra-eclipse U light level of the system. Relative to the total extra-eclipse level of the system, the K star's contribution at this phase was 0.44, because the entire disc of the K star was visible and it was contributing its maximum amount possible: 0.44 of the total extra-eclipse U level. Relative to the total extra-eclipse U light level 0.45 remained for the G star to contribute. For the emissionless profile at this phase, the G star's U continuum level was therefore scaled at 0.45; and the K star's, at 0.44. The sum of their continuum levels then equalled 0.89, the total U continuum level visible at that phase relative to the total extra-eclipse U continuum of the system. The intensity at each wavelength in each emissionless profile for each star was proportionately scaled to the U continuum contribution from that star.

The disc-fraction rule does not obtain during secondary minimum, when the G star is occulting part of the non-uniform K-star's disc and the K-star's limb darkening therefore comes into play. During ingress and egress of secondary minimum, the U continuum of the system is at a higher level than it would be if the luminance of the K star

were uniform (because the light lost by occultation of the K star's limb is only 20% of what would have been lost if the star were uniform). Conversely, during mid-secondary eclipse, the U continuum of the system is at a lower level than it would be if the K star were uniform in luminance (because the bright center of the K star is being occulted, leaving visible only the limb, which is 80 less luminous than the disc-center).

Even though the disc-fraction rule does not obtain in these instances, once the proper proportions of light are determined for each star, the intensity at each wavelength in the absorption profile of each star is, as usual, proportional to that star's fractional U continuum contribution normalized to the total extra-eclipse U continuum of the system. In this case it would be each star's fractional "limb-darkened U continuum contribution." If the limb darkening of the K star had been ignored, errors from negligible to approximately 3% for ingress and egress of secondary minimum and of approximately 3% for phases within secondary minimum would have been incurred in the equivalent widths of the K emission, the magnitude of the error depending on the amount of surface area occulted (i.e., on phase) and on the value selected for the limb darkening coefficient.

The value determined by Chambliss for the K star's limb darkening and that used in the present investigation for the G star's limb darkening are admittedly somewhat unrealistic.

Inclusion of a (probably reasonable) G star limb darkening factor of 0.5 in the present calculations would only lower somewhat the values of the K-line emission calculated for the partial phases of primary eclipse, a consequence which would have no effect on the general behavior of the emission during primary eclipse, on the general conclusion reached, or on the model formulated. Omission of the G star's limb darkening generates errors ranging from negligible to almost 30% in the equivalent width of the emission for the partial phases of primary eclipse, the error depending, as previously stated, upon the phase and upon the value selected for the limb darkening coefficient.

Chambliss (1976) also acknowledged a general problem encountered with limb darkening and gravity brightening in the G star of AR Lac. The assumption of the standard cosine law of limb darkening and of a uniform variation of flux with gravity does not represent the actual fall-off in luminance at the limb of that star or the gravity-variation of luminance over the surface of that star because the star has large dark spots--discontinuous concentrated areas of light-diminution rather than a continuous decrease in light level as the limb is approached. The proper functional dependence for limb darkening is unknown. Gravity brightening was ignored in the present calculations.

In summary, the appropriate photometric scaling criteria for each phase were used to scale the emissionless profiles for each star at each phase. The two scaled

emissionless profiles were then centered on each other, Doppler-shifted by the proper amount to account for the relative radial velocity at that phase, and finally graphically added to obtain the combination emissionless profile due to the contributions of both stars at that phase. Radial velocity curves obtained by Harper (1933) were used to determine the Doppler shift of the K star relative to the G star at each phase. Harper's curves were selected because they appeared to be the more reliable of the two sets of curves available, the others being those of Sanford (1951).

Profiles of the K-line emission

The profile of the K-line emission at each phase was determined by graphically subtracting the properly scaled combination emissionless profile from the properly scaled actual (absorption-plus-emission) profile at that phase. (See Figure 2.) Somewhat similar Ca II emission profiles are found in Greenstein (1960).

The equivalent widths of the K-line emission

As previously stated and applied, the profile of a spectral line is the graph of the ratio of the line intensity at each wavelength in the line to the intensity of the nearby continuum; i.e., the spectral intensities are normalized to the continuum intensity.

A measure of the strength of a spectral absorption line is its total absorption relative to the level of the nearby continuum. Graphically speaking, it is the area which the

line profile subtracts from the nearby continuum. In order to express line strengths independent of instrumental effects such as diffraction and finite resolving power, the artifice of the equivalent width was devised (Aller, 1951; Stromgren, 1951; Thackeray, 1961).

The equivalent width (W) of a spectral line is the width (in wavelength units) of a rectangular line of zero residual intensity relative to the local continuum and of the same area as the actual line. In other words, the line of equivalent width W absorbs the same amount of intensity from the continuum as does the actual line profile. The graphical representation of the equivalent width of a line is a perfectly black rectangular profile extending from zero intensity to the level of the local continuum and of the same area as the line profile (Stromgren, 1951; Aller, 1951). In equational form,

$$W = \int_{\lambda_1}^{\lambda_2} \frac{I_{CONT} - I_\lambda}{I_{CONT}} \, d\lambda = \int_{\lambda_1}^{\lambda_2} \left[1 - \frac{I_\lambda}{I_{CONT}} \right] d\lambda ,$$

where

W = equivalent width of the spectral line (A),

I_{CONT} = intensity of the local continuum (ergs/cm^2/sec) (Jones, 1931, 1934),

I_λ = intensity at wavelength λ (ergs/cm^2/sec),

λ_1, λ_2 = short- and long-wavelength extremities of the line profile at the level of the local continuum (A).

Investigation of the strengths of the emission reversals in absorption lines necessitated the determination of the equivalent widths of the emission alone. The equivalent width of the emission profile (W_e) at each phase was calculated by subtracting the equivalent width of the scaled combined emissionless profile (W^-) for that phase from the equivalent width of the scaled actual (absorption-plus-emission) profile (W^+) for that phase:

$$W_e = W^+ - W^-,$$

where

$$W^+ = \int_{\lambda_1}^{\lambda_2} \left[1 - \frac{I_\lambda^+}{I_{CONT}}\right] d\lambda ,$$

$$W^- = \int_{\lambda_1}^{\lambda_2} \left[1 - \frac{I_\lambda^-}{I_{CONT}}\right] d\lambda ;$$

therefore

$$W_e = \int_{\lambda_1}^{\lambda_2} \frac{I_\lambda^-}{I_{CONT}}\, d\lambda - \int_{\lambda_1}^{\lambda_2} \frac{I_\lambda^+}{I_{CONT}}\, d\lambda .$$

From this expression for W_e it can be seen that it was not necessary to actually calculate W^+ and W^-, but only to subtract the relative intensities of the absorption-plus-emission profile and the emission profile, a method which greatly simplified the calculations.

Because no equation was known for relative line intensity as a function of wavelength, the integration was performed numerically by the rectangular method:

$$W_e = \left[\sum_{i=1}^{n} \left(\frac{I_{\lambda^-}}{I_{CONT}} \right)_i - \sum_{i=1}^{n} \left(\frac{I_{\lambda^+}}{I_{CONT}} \right)_i \right] \Delta\lambda,$$

where

$\left(\frac{I_\lambda}{I_{CONT}} \right)_i$ = intensity at wavelength λ_i relative to local U continuum (dimensionless),

$\Delta\lambda$ = wavelength increment between wavelengths at which relative intensities are measured; $\Delta\lambda$ = 1.2 A = chart resolution limit.

Because the chosen integration step-size (1.2 A) was smaller than the resolution limit of the IIa-O plates at 128 A/mm (2.3 A), a more exact numerical method (e.g., Simpson's one-third rule) was unwarranted because it would have produced more precision in the result than was inherent in the data.

The equivalent width of the K-line emission at each phase is tabulated in Table 3, Section IV.

Determination of error in the equivalent widths of the K-line emission

Sources of error in the calculations of the equivalent widths of the K-line emission were

(1) photographic errors, including emulsion grain clumps, non-uniform emulsion density, and sensitometry methods
(2) electronic noise in
    (a) the recording microdensitometer
    (b) the chart recorder
    (c) the transmission densitometer
(3) the plotting of points for graphs and the reading of points from graphs
(4) variations in light curves and scatter of photometric data points
(5) the photometric distortion wave
(6) the wavelength scale for the recorder chart
(7) the radial velocity curves.

Errors incurred due to photographic grain clumps or non-uniform density were minimized by tracing the spectrograms with a slit of the greatest height and width possible without incurring degradation of resolution within the line profile. Errors from these sources were therefore rendered negligible. Sensitometry errors were of unknown, but probably small, magnitude.

Electronic noise was smoothed by averaging multiple tracings of each spectrogram. All of the tracings of any one spectrogram were virtually identical. Use of their average therefore generated negligible error.

Plotting of points and construction of smooth curves through those points was performed with very fine-pointed writing instruments on graph paper of a scale large enough to represent the precision of the raw data. Readings of points from graphs were made to the same precision as that to which the points were plotted.

The error ultimately calculated for the equivalent widths is an internal error only, generated by the method employed to obtain and analyze the data; i.e., it is not an error relative to any absolute standard.

Error analysis was carried out by two methods:
(a) "Data analysis method": The mathematical rules for error analysis were applied to the values computed in successive intermediate calculations leading to equivalent width, a procedure which incurred compound errors propagated by the mathematical operations on the inexact values which were employed in the calculations. The error for each spectrogram depended upon the particular values used in the calculation of its equivalent width. In order to demonstrate which changes in equivalent width with phase exceeded the normal computational error (i.e., were "real" changes in equivalent width), it was sufficient in this investigation to calculate only a maximum error for all spectrograms. If this calculation had proved insufficient for the determination of the validity of a particular equivalent width, the necessary individual error would have been computed. The itemized list of the errors computed by

this method is as follows:

(1) The calculation of the photographically normalized values of the relative intensities resulted in a maximum error of ± 2.0%. This value includes the errors incurred by plotting and reading data points on graphs.

(2) The combined photometric errors (due to individual variations in light curves, scatter, and the distortion wave) in the U light curves used to photometrically normalize the U continua of the spectrograms contributed a maximum error of ± 0.3% in the relative photometric intensities of the spectrograms.

(3) The error in the calculated value of the wavelength scale for the recorder chart was ± 4.7%.

(4) The error in the radial velocities contributed negligible error to the calculated Doppler shifts.

(5) Because all of the quantities containing these errors were multiplied or divided to obtain the equivalent width, the combined error was their sum: ± 7.0%.

(b) "Noise-lobe" method: By assuming that all lobes on the actual profiles were noise, maximum and minimum values for the K-line emission equivalent width were calculated. The maximum profile was constructed by inscribing on the photometrically scaled actual profile a smooth inner envelope which eliminated all intruding lobes. The minimum profile was constructed by circumscribing a smooth outer envelope which eliminated all extruding lobes. Subtraction of the areas subtended by these two profiles and division of

this difference by two yielded for each plate a sort of average equivalent-width error (in A). In general, this method produced errors far greater than the maximum 7.0% computed by the data analysis method. Because the lobes of the actual profiles appear in virtually every spectrogram, regardless of phase, it seems rather unlikely that they are noise. (They are, in fact, merely some of the many unidentified lines which are at wavelengths in the vicinity of the H and K lines and which are blended with them. No correction for them was applied, and no attempt was made to subtract them from the line profile; therefore they, too, contribute to the W_e measurements' being relative rather than absolute.) This method is deemed, therefore, to provide, for the most part, a gross exaggeration of the errors incurred in this investigation. For purposes of comparison of changes in equivalent width from phase to phase, however, and in order to demonstrate beyond any reasonable doubt the mathematical significance of the differences in the calculated values for the equivalent widths at different phases, this method is useful. Where any question might arise regarding the mathematical validity of stating that a difference exists between two equivalent widths, this extreme method can be used to demonstrate unequivocally that the difference is well above any reasonably assumed value for a noise level.

The results of the equivalent-width calculations for AR Lac are summarized in Table 3, Section IV.

SECTION IV
DISPLAY AND ANALYSIS OF REDUCED DATA

Data Display: The Graphical Relation

General Description

A graph (Figure 3) was constructed to display the relation between the relative K emission-line equivalent width and the orbital phase of the AR Lac system (data in Table 3). Data points were connected in order of phase by dotted lines merely to illustrate the general contour of the relation and to facilitate the visual scanning of the emission changes, rather than to imply the graphical representation of a function W(phase). There are too few data points over large spans of the domain to be able to graphically or equationally represent a true functional dependence. Line-terminated error bars indicate for all data points the ± 7.0% variation in K emission-line equivalent width as computed by the data-analysis method. Circle-terminated error bars indicate the non-constant variation as computed by the noise-lobe error method, which was employed only when necessary to establish beyond any reasonable doubt whether a particular data point lay within data noise or was instead indicative of a real departure from the general trend of equivalent widths in that phase region.

Table 3
RELATIVE EQUIVALENT WIDTHS OF THE Ca II K-LINE EMISSION IN AR Lac

Phase	Plate	Epoch (year)	W_e (A)	±7.0% Error (A)
.002	34	1976.6130	5.49	0.38
.060	56	1977.6989	15.20	1.06
.115	57	1977.7318	8.26	0.58
.130	58	1977.7536	11.10	0.78
.377	60	1977.9071	12.20	0.85
.384	45	1976.9402	17.35	1.21
.385	24	1976.5663	11.78	0.82
.406	18	1976.5555	14.59	1.02
.415	46	1976.9403	19.69	1.38
.456	41	1976.6209	16.79	1.17
.458	37	1976.6155	17.27	1.21
.498	38	1976.6157	14.71	1.03
.504	42	1976.6211	15.28	1.07
.560	50	1977.0605	20.19	1.41
.724	59	1977.7895	12.15	0.85
.857	61	1977.9097	13.19	0.92
.902	21	1976.5637	12.36	0.87
.923	28	1976.6017	17.34	1.21
.939	33	1976.6127	12.01	0.84

Phase: fraction of the period of revolution of the system

Plate: the ordinal number of the plate, indicating the temporal order in which it was obtained

Epoch: the epoch of the observation, listed as the year and the day + month + hour of the observation as a decimal fraction of a year

W_e: the relative equivalent width of the K-line emission at the corresponding phase, in A

$\pm$7.0% Error: 7% of W_e, the error determined by the "data analysis method," in A

See Figure 3.

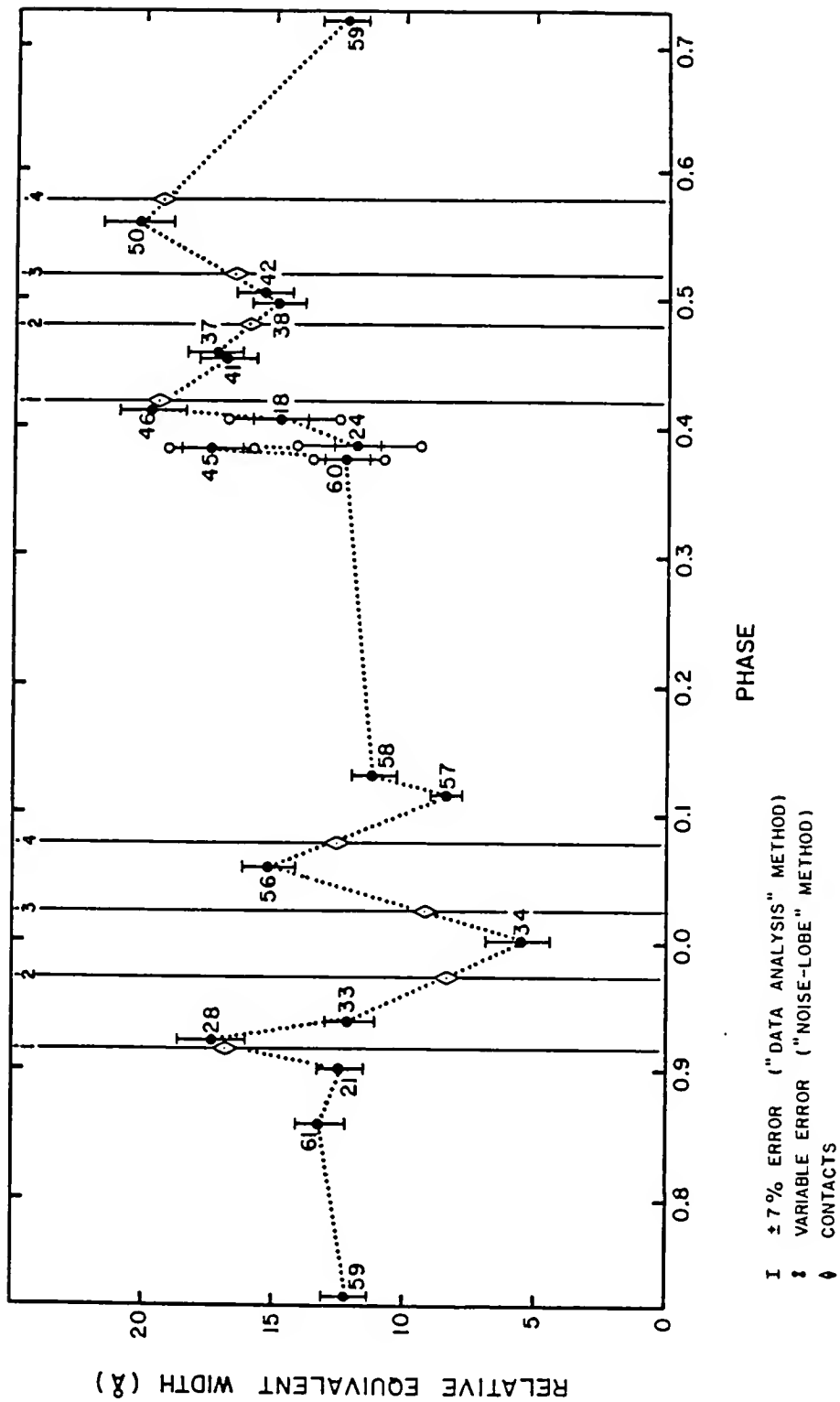


Figure 3
VARIATION OF THE RELATIVE EQUIVALENT WIDTH OF THE Ca II K-LINE EMISSION WITH ORBITAL PHASE IN AR Lac

A cursory comparison of the error bars for all the data points indicates that the emission exhibits prominent eclipse features (local relative minima in the emission) and some extra-eclipse variations.

Eclipses of the Emission

Well-defined eclipse minima in the emission and pronounced near-symmetry about the mid-eclipse phase characterize both primary and secondary eclipses. Phases were computed using the ephemeris in Hall, Richardson, and Chambliss (1976).

Primary eclipse

From the graph it is seen that as primary eclipse is approached, the emission level dips slightly just prior to first contact, then rises to a local maximum at first contact. This maximum is followed by a sharp decline to a mid-eclipse local minimum, which lies well below the pre-eclipse emission level. Following mid-eclipse is a rise to a local maximum just prior to fourth contact, a subsequent decline to a local minimum lying above the mid-eclipse level, and a sharp rise to a post-eclipse level slightly below the pre-eclipse level. The existence of the pre-ingress depression in the emission is somewhat doubtful because the error bars of the two adjacent data points (#61 and #21) share some common ground. The post-egress depression may be a real phenomenon rather than noise, because there is a lack of commonality in the error bars of the three data points (#56, #57, and #58) which define it.

The data exhibit a lack of perfect symmetry about mid-eclipse. The existence of near-symmetry strongly suggests that symmetry does exist, but is in some manner veiled. The veiling agent is probably a selection effect: namely, that data were obtained only at certain phases, which were not chosen for their symmetry about mid-eclipse. The presence of additional data points at phases symmetrical relative to mid-eclipse would probably reveal the suspected symmetry. In further support of this suggestion it is noted that there is a large span (0.04 phase unit) between the two points defining pre-ingress depression (#61 and #21), whereas there is only 0.015 phase unit between the two post-egress plates (#57 and #58). If it can indeed be contended that the depressions are symmetrical (and there is nothing in these data or in those of others to preclude symmetry), then between #61 and #21 there could be a much lower value of equivalent width (at about phase 0.885) similar to that of #57.

The lack of symmetry between the levels of pre- and post-depression emission levels can also probably be attributed to the paucity of data points at symmetrical phases relative to primary mid-eclipse. A data point at phase 0.14 (just beyond #58) might well have returned to the pre-ingress level. No concrete conclusion can be drawn regarding perfect symmetry without additional data at the required phases.

Within primary eclipse the ratio of maximum emission to minimum emission is 3.7, maximum occurring at first contact and minimum at mid-eclipse. The ratio of maximum emission to the average extra-eclipse level (at the shoulders of the pre- and post-eclipse depressions) is 1.4. The ratio of the average extra-eclipse level to the minimum emission level is 2.4. The minimum emission level at mid-eclipse is the absolute minimum for the entire orbital cycle.

Secondary eclipse

As secondary eclipse is approached on the graph, the emission rises to a local maximum prior to first contact (at phase 0.384). (See Extra-eclipse Behavior.) The emission then declines to the previous level before rising to a slightly higher local maximum at first contact. Following first contact is a decline to a mid-eclipse local minimum, which lies slightly above the pre-eclipse level. Nearly mirroring this behavior (viz., with the omission of the pre-ingress maximum) is a post-mid-eclipse rise to a local maximum just prior to fourth contact and a subsequent decline to the pre-ingress emission level.

As in the case of primary eclipse the question of perfect symmetry arises, and the reply is the same: more data points near fourth contact are needed to confirm or deny symmetry.

Within secondary eclipse the ratio of maximum emission to minimum emission is 1.3, maximum occurring at first contact and minimum at mid-eclipse. The ratio of maximum

emission to the extra-eclipse level is 1.6. The ratio of the minimum emission to the extra-eclipse level is 1.25.

Comparison of primary and secondary eclipses

The eclipse of the emission is much shallower, both absolutely and relatively, at secondary minimum than at primary minimum, the mid-eclipse emission level of the former being 2.8 times higher than that of the latter. Because secondary eclipse is central, but not total, the emission at secondary mid-eclipse is composed of contributions from both stars. On the other hand, during primary eclipse the G star is completely occulted; therefore the emission at mid-primary eclipse is contributed by the K star alone.

Extra-Eclipse Behavior

With the exception of plates #45, #57, and #61 the ranges of error for the extra-eclipse plates indicate a virtually constant extra-eclipse emission level. There are, however, very few extra-eclipse plates; therefore no general conclusive statements can be made regarding extra-eclipse behavior.

Coverage in the vicinity of phase 0.384 (plates #60, #45, and #24) is, however, sufficient to state that there is an emission peak at that phase. Comparison of error bars (even the exaggerated ones determined by the noise-lobe error method) demonstrates that the peak rises significantly above the noise level.

Interpretation of the Graphical Relation

Variability of the Emission

Performed as an internal check of the consistency of the spectrograms with the emission profiles, microscopic visual examination of the plates revealed that the Ca II emission is visible at all phases. It is not entirely eclipsed at either minimum, thereby corroborating Sanford's (1951) and Weiler's (1978) observations that the emission is present outside of as well as within eclipse. The difference between equivalent widths of adjacent data points of the equivalent width-phase curve exceeds the computed range of error, even when the more extreme of the two error calculations is considered. The emission is therefore very definitely variable, in confirmation of the observations of Sanford (1951), Babaev (1974c), Weiler (1975, 1978), and Naftilan and Drake (1977), and the conclusion of Kron (1952) upon examination of Wyse's (1934) plates. Further, the variations appear to be phase-dependent and/or time-dependent, not random, as reported by Weiler (1978) and as indicated by Babaev's (1974c) data.

Relative Strengths of the Emission

Because the grating dispersion used in this investigation was not great enough to resolve the components of the K line from each star, the emission in the graphical relation represents a composite of the emission from both stars. Consequently, no statements can be made in confirmation or denial of Sanford's (1951) observations that

the ratio of the secondary's emission to the primary's emission increased during the first half of the system period and decreased during the second half of the period. Again because of insufficient dispersion, no positive or negative statements can be made regarding confirmation of the observations of Sanford (1951) and Naftilan and Drake (1977) that the emission from the secondary star is stronger than that from the primary star.

Attempts to reconcile the intra-eclipse behavior of the graphical relation of this investigation with the intra-eclipse observations of Sanford (1951) and Naftilan and Drake (1977) appeared to fail at first glance. Examination of their K-line profiles at primary and secondary mid-eclipse revealed a higher level of emission at primary eclipse than at secondary eclipse, whereas the present investigation indicated just the opposite.

This problem was resolved upon closer inspection of the manner in which both of the previous investigators analyzed their data. These observers performed their calculations of the equivalent width of the emission at a given phase by comparing the intensity of the emission to the intensity of the continuum level <u>at that phase</u> rather than by comparing the emission to an absolute, unchanging <u>continuum standard level</u> (as was done in the present investigation).

As seen in Sanford's (1951) line tracings, it is indeed true that at primary minimum the emission rises above the continuum level; whereas at secondary minimum the emission

does not quite reach the level of the continuum, both emission peaks being the same width at the base. The continuum level at primary mid-eclipse is, however, only 54% of the continuum level at secondary mid-eclipse (Chambliss, 1976). When the equivalent width of the emission for each star was calculated using their data, but comparing both emission levels to the same standard continuum level (the extra-eclipse level), the same conclusion resulted as was obtained in the present investigation: the equivalent width of the emission is greater at secondary mid-eclipse than at primary mid-eclipse.

Sanford's and Naftilan and Drake's conclusion that the emission of the primary star is weaker than that of the secondary star remains unchanged by the above-instituted change in the level of the continuum to which the emission was compared because the dispersion they used was great enough to completely resolve the emission components from the primary and secondary stars, thereby allowing direct comparison of the relative amounts of emission from both stars at each phase (except at eclipses).

Observed Surface Distribution of the Emission

There is considerable evidence, both direct and indirect, that the emission is not uniformly distributed over the surfaces of the stars in AR Lac. Extra-eclipse variability seen by previous observers and in the present investigation constitutes evidence of non-uniformity of emission.

For a number of Ca II emission stars, Struve (1945), Hiltner (1946), Struve (1946), and Gratton (1950) found evidence favoring the permanent localization of the emission at the tips of the tidal bulges of the star(s) producing the emission. Struve (1948), although acknowledging that the localization of the emission of AR Lac had not been investigated, inferred that it was confined to the tidal bulges by analogy with RZ Cnc and RW UMa.

Weiler (1978) suggested that his observation of a substantial change in the equivalent width of the emission over a short period of time during the partial phases of secondary minimum ingress (a diminution of 4A in 35^m) could be indicative of "the eclipse of a localized emission area on the K0 IV star" (Weiler, 1978, p.88) because this dramatic change could not be explained by the eclipse of a uniform distribution of emission over the stellar surface.

Sanford (1951), Struve (1952), and Naftilan and Drake (1977), on the other hand, found that the broadening of the Ca II emission in AR Lac corresponds to synchronous rotational broadening, thereby indicating that the emission emanates from all parts of the stellar surface(s) or at least from complete equatorial bands. Kron (1952) had concluded that the distribution of the emission around the entire equator of the star does not necessitate that the distribution be homogeneous--the emission could be concentrated in patches well distributed in longitude and not fixed permanently in certain areas.

The asymmetry of the line profiles in the present investigation provides a piece of evidence that the distribution of light over the stellar surface is non-uniform (Huang and Struve, 1960). The variations in the emission in the vicinity of the eclipses and the emission peak at phase 0.384 indicate the presence of strong, localized emission sources. The presence of the emission throughout the system's cycle indicates that there is also probably some distribution of emission over the entire equatorial region or the entire surface(s) of the star(s).

The exact nature of the emission source(s) (size, position, distribution) is uncertain from the data in this investigation because there is insufficient time/phase resolution in the vicinity of each contact and insufficient spectral resolution overall. Better resolution would establish more precisely the changes in the emission as it is eclipsed so that an accurate determination could be made of the phases at which the emission decrease begins and ends during each eclipse.

Model for the Surface Distribution of the Emission

A model was constructed to account for the observations in this investigation. A model with uniform distribution of emission could not explain the character of the variations in the emission; therefore a model with non-uniform emission was chosen--a composite incorporating three emission sources:

(1) distributed emission from all parts of the stellar surfaces or at least from complete equatorial bands, the emission arising from well-distributed spots or patches

(2) strong emission permanently localized at the extremities of the tidal bulges of the stars

(3) strong emission from a localized source other than the bulge-extremities.

The distributed emission accounts for the presence of the underlying "background" of emission observed in this investigation throughout the system's cycle and also for the observations (Sanford, 1951; Struve, 1952; Naftilan and Drake, 1977) that the broadening of the emission corresponds to that which would be observed from a source which spans the full diameter of the star rather than being concentrated only in a small area.

The presence of emission sources at the extremities of the tidal bulges explains most of the observational features seen in this investigation in the vicinity of and within eclipse (see Primary eclipse). Compatibility of the results of this investigation with the observations of Sanford (1951) and Naftilan and Drake (1977), who determined that the emission from the K star (the secondary) is numerically greater than that from the G star, requires the sum of the emission from the sub- and anti-stellar bulges of the K star (K_S and K_a) to be greater than the sum of the emission from the sub- and anti-stellar bulges of the G star (G_S and G_a).

The non-bulge localized source accounts for the emission peak at phase 0.384.

Model for the Generation of the Observed Behavior of the Emission with Phase

Combination of the model pictured above with the system motion revealed the details of the explanation of the equivalent width-phase relation.

Primary eclipse

This model cannot explain the pre- and post-primary-eclipse emission depressions because severe contradictions are encountered. The explanation for these depressions is therefore left to circumstellar matter and a consequent increase in absorption rather than a decrease in emission. (See Correlations of Photometry and Spectroscopy.)

An increase in the visible area of the emission concentration of the substellar bulge (G_s) of the G star and on the antistellar bulge (K_a) of the K star as the stars revolve accounts for the pre-first contact increase in the emission prior to primary eclipse.

The first-contact emission maximum occurs because more of these two areas is visible than at any other phase (except fourth contact). Comparison of the emission level at this maximum to the emission at the quadratures (when one-half of each emission area is visible) leads to the conclusion that the sum of the substellar emission (G_s) from the G star and the antistellar emission (K_a) from the K star is greater than the sum of the anti-stellar emission (G_a)

from the G star and the substellar emission (Ks) from the K star. This result is compatible with the results of Sanford (1951) and Naftilan and Drake (1977) if the substellar emission (G_s) of the G star is greater than or equal to the substellar emission (K_s) of the K star. (There is no evidence to preclude this possibility.)

The post-first contact decline in emission can be attributed to the eclipse of the substellar emission (G_s) of the G star while the contribution from the antistellar bulge (K_a) of the K star remains constant (because the entire area of this emission is visible from first to fourth contact). Between second and third contacts the emission is entirely due to the anti-stellar area (K_a) on the K star.

The emission increase to a maximum at fourth contact is caused by the reappearance of the substellar emission (G_s) of the G star while the emission from the K star remains constant.

The post-fourth contact decrease in emission occurs as the K-star anti-stellar emission (K_a) area and the G-star substellar emission (G_s) area are disappearing around the limb.

Secondary eclipse

The increase to a maximum at first contact of secondary eclipse is caused by more of the K-star substellar emission (K_s) area and more of the G-star antistellar emission (G_a) area rotating into view. At first contact the maximum amount of both of these areas is visible.

Examination of the graphical relation shows that the first-contact maximum of secondary eclipse is greater than that of primary eclipse. This observation leads to the conclusion that the sum of the anti-steller emission (G_a) from the G star and the substellar emission (K_s) from the K star is greater than the sum of the anti-stellar emission (K_a) from the K star and the substellar emission (G_s) from the G star. This contradiction of the conclusion drawn during primary eclipse can be resolved if K_a and G_s are <u>not</u> wholly visible at first contact of primary eclipse, but K_s and G_a <u>are</u> wholly visible at first contact of secondary eclipse.

The emission decrease to a minimum at mid-secondary eclipse is explained by K_s beginning to be eclipsed while G_a remains in full view. The emission does not decline to as low a level as at mid-primary eclipse either because (1) K_s is not completely eclipsed or because (2) G_a is greater than K_a if K_s is completely eclipsed. (A definite choice cannot be made until the size of the K_s emission area has been measured.) The only positive statements which can be made are that G_a plus the contribution from the K star (if any) at mid-secondary is greater than K_a and greater than the emission level at the quadratures.

The post-mid-eclipse emission rise to a maximum at fourth contact occurs as K_s reappears from eclipse and G_a remains constant. At fourth contact (as at first contact) both K_s and G_a are entirely visible, therefore producing a

maximum. The emission declines after fourth contact as a result of these emission areas on both stars rotating around the limb.

Extra-eclipse behavior

There are at least four ways in which the extra-eclipse emission maximum at phase 0.384 could be interpreted:

(1) anisotropic emission of a highly directional nature (designated the anisotropic model)

(2) a phenomenon of short time duration and fixed surface position (designated the temporal model)

(3) a phenomenon of short time duration due to rotation of surface position (designated the spatial model)

(4) combinations of these.

Anisotropic model. The anisotropic model is rather unlikely because there are no examples of Ca II emission which is quite so directional as to cause such a sharp spike (except perhaps some sort of Cerenkov radiation possibly associated with the radio emission from AR Lac: Smith, 1983. See Radio emission, esp. Owen and Sprangler, 1977.) In the sun, for example, Ca II emission can be observed from all sunspot areas, be they mid-disc or near the limb. St. John (1910) found that the measurement of the widths of the Ca II lines at mid-disc was not generally possible, but the intensity of the Ca II emission near the limb was "very much greater than over the general disk" (St. John, 1910, p. 64). The emission did not, therefore, become stronger when

the emitting areas were observed on the normal than when they were observed at an angle to the normal.

Temporal model. Temporal events include formation and dissolution of an emission region (a starspot or starspot group), the occurrence of a flare (or flares), and general trends in emission level over several cycles or epochs.

The extra-eclipse peak observed in this investigation extends over a phase interval from phase 0.377 (plate #60, epoch 1977) to phase 0.385 (plate #24, epoch 1976). The width of the base of the peak is 0.008 phase unit, which is equivalent to 23^{m} of time. The maximum of the peak lies at phase 0.384 (plate #45, epoch 1976). The emission intensity of the peak maximum rises well above the levels of the two flanking plates, their intensities being almost identical. The error bars confirm this event as a real phenomenon. The plates were obtained in the numerical order indicated by their plate numbers.

The three spectra which define the peak observed in this investigation were not obtained during the same cycle of AR Lac or during the same epoch of observation, and the chronological order of the plates is not in order of increasing phase. For these reasons this peak cannot be interpreted in a simple phase-sequenced temporal sense: that is, as the observation of the entire or partial sequence of events in any short-term phenomenon, either as (1) the formation and dissolution of an emission region or as (2) the rise and fall of emission during a flare.

Observation of either a starspot (or group) or a flare at one point (plate #45) in the midst of activity is, however, an acceptable interpretation for the event observed in this investigation.

Babaev (1974c) made a similar observation of a peak at phase 0.6489 and of width 0.1429 phase unit (equivalent to $6^h.8$ of time). These dimensions were derived upon the assumption that the emission portion of the K-line maximum he observed had the same width in phase units as the composite (emission-plus-absorption) curve shown in his paper. The same conclusions as were drawn in the present investigation must be drawn regarding Babaev's peak, but for a different reason: viz., that he made no mention of the date(s) on which his observations were made, so that no temporal continuity can be assumed.

The fact that neither of these observations can be explained by either the starspot formation and dissolution picture or the flare picture does not, per se, preclude the occurrence of such events in AR Lac. Further considerations are necessary in order to accept or reject these pictures. For this gedankenexperiment it was assumed that all of the data in each investigation cited above were obtained in temporal order during the same cycle of the system. The starspot model would not provide a valid interpretation of these observations because the time intervals involved are far too brief (by a factor of 40 at the minimum, when compared to sunspot durations) for spots to form and

dissipate. (No theory is presently available, however, by which to determine whether this short a duration time for a starspot could occur in the RS CVn stars.) On the other hand, these hypothetical data would lend themselves well to the flare interpretation because events of similarly short time duration, suspected of being flares, have been observed in AR Lac, SZ Psc, SV Cam, and other binaries. Weiler (1978) observed the pronounced diminution of the H and K emission of AR Lac over a period of only 35^m during the partial phases of secondary eclipse. Because the decrease was nearly seven times what would be expected from the geometrical effects of eclipse, he interpreted the event as the eclipse of a localized emission area (a relatively long-term phenomenon--a spot). He might just as easily have been observing the occultation of a flare-in-progress (in contrast, a short-term event). Caton (1981) concluded that if the scatter in Jakate's (1980) photometric observations of SZ Psc is indeed above the noise level, it may provide the first observational evidence of optical flaring in RS CVn stars. Suspected flares of approximate duration 45^m were observed in SV Cam by Patkos (1981). Hall (1976) considered that flares in RS CVn stars might well occur, but not be observed because these systems are brighter than the RS CVn-related dMe and dKe systems in which flares are observed to occur. Naftilan and Drake (1977) observed in the H and K emission of AR Lac short-term variations which they considered as indicative of an active chromosphere.

These rapid variations could perhaps also be interpreted as evidence for the occurrence of flares.

Because plates #24 and #60 fall at almost exactly the same emission level over the course of two epochs (1976 and 1977, respectively), their level can probably be considered to be the usual level of emission for AR Lac in that phase region. The change in emission level represented by the elevated value of plate #45 (epoch 1976) cannot, therefore, be interpreted as the onset of a general trend toward lower emission level in that phase region in successive system cycles or epochs. (Because the stars in the AR Lac system are intrinsically variable, however, it is probably not wise to assume generally that any level is constant with either time or phase.)

Spatial model. The spatial model consists of the interpretation of the width of the emission peak as a phase interval of emission visibility which is produced as the active region which generates the emission is being carried into and out of view by the rotation of the star upon which it resides. The width of the peak in phase units determines the time interval during which the region is visible. Included in this model is the assumption that such an event does not repeat itself identically in successive cycles, so that it would not be possible to catch later on what was missed at some phase in an earlier cycle or epoch. In other words, the assumption is that the activity does change in position and phase. (The width of the photometric

distortion wave maximum or minimum could perhaps also be interpreted in this manner.)

The same opposition is raised regarding the spatial model for the peak observed in this investigation as was raised regarding the simple phase-sequenced temporal model: viz., the observations were not made in chronological order, nor were they closely spaced temporally. The observation of the maximum of the peak could, however, be interpreted as being just one moment of a spatial event.

As in the temporal case the inability of this model to explain this particular set of observations does not in itself rule out the occurrence of such events in AR Lac. In order to determine the validity of such a suggestion, it must first be determined whether such an event is within the limits of observability (as was done in the temporal case). A photometric analogy is utilized to serve this purpose. Caton (1981) determined by a computer-generated model that a group of cool starspots observed together on the stellar surface would indeed produce a visible phenomenon: the light-level diminution known as the photometric distortion wave. When the spot group passes around the limb or is eclipsed, the light level rises again to its usual level. The observation of this phenomenon in AR Lac was first announced by Chambliss (1975b). It has since been studied by several observers. If Caton's result can be extended to Ca II emission regions, then it could be concluded that a group of emission areas observed together on the surface

would produce an emission peak. No analysis similar to Caton's photometric analysis has been performed to determine the theoretical visibility of Ca II emission regions. Babaev (1974c) may well have observed such a spatial event if his observations were indeed made in chronological order and were closely spaced in time. Weiler's (1978) observation of the rapid and considerable emission decrease during secondary eclipse phases may also provide an example of an observation of the eclipse of a Ca II emission region or group, just as he interpreted it. No follow-up observations were made, however, to verify whether the feature is a permanent one (fixed in the same position on the star) or a semi-permanent one (changing in latitude, longitude, or phase) of some duration.

Visibility of the phenomenon having been tentatively established, a physical model to explain how the star would produce such an event must be formulated, as was done in the temporal case. For the sake of simplicity the emission peak was assumed to be produced by only one of the stars in the AR Lac system. It is known that the primary (G) star is more variable photometrically than the secondary (K) star (Wood, 1946; Kron, 1947); however the Ca II emission of the secondary is stronger than that of the primary (Sanford, 1951; Naftilan and Drake, 1977). The secondary is therefore chosen as the component supposedly responsible for the emission peak. For the construction of the model it was assumed hypothetically that, as in the

temporal case, the data in this investigation and in Babaev's (1974c) observations were obtained in temporal order and during the same cycle of the system. The emitting region would therefore have been visible for an interval of 0.008 phase unit in this investigation (observations made from 1976-1977) and for 0.1429 phase unit in Babaev's investigation (observations made presumably from 1968-1972). The interpretation of the combination of these two pieces of data depends upon (1) the internal structure of the star and (2) the tidal effects of binariness, which determine the nature of the rotation of the star. In other words, whether the star has a convective or a radiative envelope and whether the star has a companion which raises small or large tidal bulges determine whether the star rotates differentially or like a solid body, respectively (Hall, 1972).

Both components of AR Lac have gravity-brightening indices consistent with deep convective envelopes (Chambliss, 1976), and the KO IV secondary is cool enough to have a deep convective envelope (Popper 1961). Hall (1972) pointed out that Huang (1966) offered the "reasonable supposition" that stars in a binary system should experience differential rotation as long as "the tidal bulge raised by the binary companion does not entirely suppress the natural tendency to rotate differentially" (Hall, 1972, p. 325). Hall therefore concluded that although the rotation of the stars in RS CVn is observed to be the same as the system

period, it does not follow that they are strictly synchronous. Synchronous rotation is merely the average of the rotation over the entire stellar surface. Neither component of AR Lac has an excessive tidal bulge--the oblateness of the primary is 0.006, and that of the secondary is 0.035 (Chambliss, 1976). AR Lac therefore conforms to Huang's description and should consequently rotate differentially.

Because there has been no theoretical model formulated for differential rotation in stars with convective envelopes, Hall (1972) suggested the sun as an example of a star with a convective envelope, after which the differential rotation of other stars with convective envelopes might be modeled. The differential rotation of the sun is such that the equator rotates the fastest, the rotation rates of other latitudes being given by

$$y = 14°44/\text{day} - 3°0 \sin^2 x/\text{day},$$

where x is the latitude and y is the rotation rate in longitude (°/day) (Allen, 1973). This solar differential rotation is observed in the motion of sunspots at different latitudes. As an average 11-year optical sunspot cycle progresses, sunspots are formed successively equatorward in latitude. This phenomenon is usually referred to as "latitudinal sunspot drift" or simply "drift." The average annual latitudinal drift rate is 1°.72/year, the drift rate decreasing as the latitude of the spots decreases (Allen, 1973).

Tentative establishment that the stars in AR Lac do rotate differentially and that the differential rotation is very likely in the same sense as that of the sun (faster at the equator) allows the interpretation of the combination of the two phase intervals of visibility of the emission region. The smaller the phase interval of visibility, the faster a feature is transiting the stellar surface due to the rotation of the star. The faster a feature transits, the closer the latitude of that feature is to the equator of the star. By this model the observed decrease in the phase interval of visibility between 1968-1972 and 1976-1977 would indicate that during this period of time the emission region had drifted toward the equator, just as sunspots do.

Because there has apparently been no general equation derived for the rate of differential rotation as a function of latitude (the rate being expressed in terms of the phase interval of visibility of the emission), it is not possible presently to calculate the latitude at which the emission area lies. It could only be stated that (1) the emission area is closer to or farther from the equator and that (2) various differential rotation rates could be measured observationally. There must, however, be some upper limit on the rate of differential rotation, so that gravitational stability within the star is maintained. An interval of 0.008 phase unit, indicating a time interval of 23^m for the region to rotate completely across the face of a star of the size of the AR Lac secondary, might be a bit on the short

side for preservation of such internal stability. This short an interval probably also indicates too great a departure from the synchronous rate for this system, this statement being based on sunspot motion on the sun as a model. The equator of the sun rotates 1.6 times as fast as the poles (Allen, 1973), whereas in AR Lac the ratio of the synchronous rotation rate to the 23^m interval is a whopping 124. Events of longer duration, such as the one which may have been observed by Babaev (duration 0.1429 phase unit, or $6^h.8$, thereby yielding a ratio of 7), might be possible.

Conclusion. Because of the lack of (1) temporally ordered observations and (2) observations repeated at the same phase in successive cycles of AR Lac, the question of whether the cited observed behavior represents (1) a feature relatively fixed spatially on the stellar surface and observable either at one phase or migrating in phase or (2) a transient temporal feature remains unanswered. Both interpretations are not only reasonable, per se, but are also supported by observations of emission phenomena which are apparently of temporal and spatial nature (flares and eclipses of emission regions, respectively) in AR Lac, other RS CVn systems, and related systems.

Correlations of Spectroscopy and Photometry

There are a number of correlations which may be made between the spectroscopic phenomena observed in this (and other) investigations and photometric phenomena observed in other investigations.

Eclipse correlation

The eclipse of the "background" K-line emission of AR Lac observed in this investigation corresponds almost exactly to the photometric eclipses of the system. (See Figure 2). Other investigators (Babaev, 1974c, and Weiler, 1978) did not find such a correlation. Instead, they observed rather random emission throughout the system's cycle. If the relative strengths of the Ca II emission from the components of AR Lac are variable with time (which seems likely), the eclipse effect could be masked, thereby allowing eclipses to be observed during some cycles and not during others. These seemingly contradictory observations would therefore be reconciled.

Pre- and post-eclipse depressions

A strong similarity between the spectroscopic and photometric behavior of AR Lac has been observed by several observers prior to and following primary eclipse. These observations suggest that the spectroscopic and photometric phenomena may have some relation, perhaps some common mechanism producing them both.

In the present investigation depressions were observed in the K-line emission of AR Lac at pre-first contact and post-first contact phases of primary eclipse (phases 0.92 and 0.115, respectively).

Kron (1947) and Catalano (1973) reported depressions in the light curve of AR Lac just before first contact and just after fourth contact of primary minimum. Kron's light curve

showed the depth of the depressions to be 0.08 mag at phase 0.817, 0.06 mag at phase 0.883, and 0.06 mag at phases 0.141-0.197. Catalano measured the depths of the depressions in his light curve to be approximately 0.05 mag (as reported by Hall, 1976).

The photometric distortion wave could not be invoked as the cause of these depressions because the distortion wave minimum was found to be at other phases of these light curves. Catalano (1973) and Naftilan and Drake (1977) therefore made the proposal that the pre- and post-ingress light curve dips might be indicative of a circum-secondary envelope. As additional photometric evidence of such an envelope, the scatter observed in the 1948 near-infrared light curve obtained by Kron indicated the presence of an extended atmosphere about the secondary star (Theokas, 1977). The system's infrared excess (Naftilan and Drake, 1977) and ultraviolet excess (Rhombs and Fix, 1977) also indicate the possibility of a circum-secondary envelope.

In this investigation as well as in that of Weiler (1978) it was assumed that any changes observed in the equivalent widths of the Ca II line profiles are due to changes in the intensity of the emission. The apparent decreases in emission in the vicinity of primary eclipse could, however, be alternatively interpreted as increases in Ca II absorption. Such absorption increases could perhaps be explained by occultation of the primary star by an absorbing envelope, as was implicated as the cause of the

photometric depressions. A further basis for this contention is the observation (Naftilan and Drake, 1977) that the H-alpha emission components of AR Lac are symmetrical about the line center of the secondary star's line profile, both within and outside of eclipse. Naftilan and Drake indicated that this symmetry lends itself well to the interpretation that it is produced within a rotating non-equilibrium envelope with two different velocity regions.

Distortion-wave-minimum--emission-maximum--period-change relation

Hall, Richardson, and Chambliss (1976) noted that for each of several RS CVn systems (RS CVn, SS Cam, RT Lac, CG Cyg, V471 Tau, and AR Lac) there is a smooth graphical relationship (a "migration curve" for each system) between the phase of the minimum of the photometric distortion wave and epoch. For each system, points representing the phases at which period changes have occurred also lie along the migration curve for that system, observed period decreases having occurred when the phase of the system was 0.25, and period increases, at phase 0.75. (See Table 4 and Figure 4 for the curve for AR Lac. For this curve the error in the phase of the wave minimum is ±0.1 phase unit.)

Period changes. An interpretation of the observations of period changes at particular phases in the migration curves had previously been offered by Hall (1972), Arnold and Hall (1973), Hall and Henry (1973), and Arnold, Hall,

and Montle (1973). The abrupt period decreases in these systems occur when the minimum of the distortion wave is at phase 0.25, which coincides with the time at which the spotted area producing the distortion wave minimum is on the leading edge of the star producing the wave. Ejection of material from this region results in the stars' moving closer together, thereby decreasing the period of the system. The sudden period increases occur when the distortion wave minimum is at phase 0.75, when the spotted area is on the following edge of the star producing the wave. Material leaving the region would cause the stars to move farther apart, increasing the period of the system.

The correlation of the phase of the distortion wave minimum and the phase of period changes allows the migration curve to be used to predict the epoch and the sense of future period changes in these systems. Hall, Richardson, and Chambliss (1976) predicted that for AR Lac a period increase had occurred in 1974 ± 3, when the minimum of the distortion wave was at phase 0.75. (No 1971-1977 data had been reduced at that time to enable them to verify their prediction.)

Later on, however, Scarfe and Barlow (1978) calculated a new period for AR Lac from their observations made sometime between 1973 and 1976. (The precise years for the AR Lac data were not indicated.) Comparison of this new period ($1^{d}.9831955 \pm 0^{d}.0000010$) to the previous period ($1^{d}.9831987 \pm 0^{d}.0000005$) calculated by using data collected

during observations from 1966-1973 and published by Chambliss (1976) yields a period decrease of $0^{s}276$. (Nha et al. (1982) also reported a period decrease, of about 20^{m}, occurring in 1977.) Chambliss' data further indicated that the phase of the minimum of the photometric distortion wave during 1973-1975 was 0.72, which should have corresponded approximately to a time of period increase according to Hall, Richardson, and Chambliss' prediction.

At first glance the results of Scarfe and Barlow and Nha et al. seem to cast doubt on the validity of the predictive ability of Hall, Richardson, and Chambliss' curve. During the time interval of the former investigators' observations however, the migration rate of the wave was changing very rapidly. (See Figure 4.) A period increase, therefore, could have occurred at the beginning of the interval (1971-1973), followed by a period decrease at the end of the interval (1975-1977). These two consecutive oppositely directed period changes might not have been observed as two separate events for two reasons: (1) the rapidity of the migration, which would result in the O - C excursions' being of very low amplitude (Hall, Richardson, and Chambliss, 1976) and therefore easy to overlook; and (2) scarcity of data at close enough time intervals to provide enough time resolution to distinguish small changes. Also, if the period decrease was slightly greater than the subsequent period increase, the net period change would be observed as a slight decrease in period,

exactly as was observed by Scarfe and Barlow. They might have observed the beginning of the period decrease, with Nha et al. observing the full effect shortly thereafter. In support of this idea, it is noted that the period changes of AR Lac are not constant: they have been observed to vary from a minimum of $0^{d}.0013$ to a maximum of $0^{d}.036$ (Hall, Richardson, and Chambliss, 1976). These variations are very probably related to the variations in the number and sizes of starspots on the stars when the wave minimum is at phases 0.25 and 0.75. A greater number of spots of greater size would eject more material, thereby producing a greater period change. Neither the results of Scarfe and Barlow nor those of Nha et al. are included in Figure 4.

Distortion wave minimum and Ca II emission maximum. Coincidence of the phase of the photometric distortion wave minimum and the Ca II emission maximum has been observed in RS CVn and UX Ari by Catalano and Rodono (1974), Evans and Hall (1974), and Hall, Montle, and Atkins (1975), all reported by Weiler (1975). If it could be shown that the phase and epoch of the emission maximum follow the same curve as the phase and epoch of the photometric distortion wave-minimum of AR Lac, then there would be a strong indication of a definite relationship between these phenomena in AR Lac also.

Weiler (1978) reported a sudden decrease in emission occurring at phase 0.47 in 1974. If this decrease could be interpreted to be a decrease from a maximum, then this

maximum could be plotted on Hall, Richardson, and Chambliss' (1976) migration curve for AR Lac to determine whether this point lies on the curve. This point fits the curve at least as well as (and in some cases better than) the photometric points which were used to define the curve. (This portion of the migration curve is not well-defined because there has been only one data point for the photometric distortion wave published for epochs later than 1974: Caton, 1981, reported that in 1979 the phase of the distortion wave minimum lay between 0.87 and 0.93. See Figure 4.)

During 1968-1972 Babaev (1974a,b,d) made photometric observations of AR Lac. His graph (1974d) of change in m_B magnitude of AR Lac versus phase exhibited a maximum at phase 0.6395 (obtained by averaging the phases of the three points defining the maximum). The peak spanned phases 0.6190-0.7097. This maximum was assumed by Hall, Richardson, and Chambliss (1976) to be the maximum of the photometric distortion wave, thereby allowing them to determine the phase of the minimum of the distortion wave to be 0.1395 by subtracting 0.5 phase unit from the phase of the maximum. (Hall, Richardson, and Chambliss used phases 0.65 and 0.15, respectively; however the actual peak shown in Babaev's table of data is at phase 0.6293, and the region of maximum is defined by two other points, at phases 0.6393 and 0.6499.) Presumably also during 1968-1972 Babaev (1974c) made his spectroscopic observations of AR Lac, although no years were specified for these observations.

His graph of K-line equivalent width versus phase exhibited a pronounced maximum at phase 0.6489. The peak occupied the phase interval 0.5785-0.7214, and corresponded to a maximum in absorption, a minimum in emission. Comparison of Babaev's photometric and spectroscopic data revealed that the photometric wave maximum and the emission minimum coincided in phase because their phase intervals overlapped. If it can be construed that this occurrence implies that the photometric wave minimum coincides with the emission maximum, then the desired correlation is demonstrated between the photometric and spectroscopic phenomena. Upon the assumption that the latter relationship is valid, points were plotted for Babaev's distortion wave minimum and emission maximum on Hall, Richardson, and Chambliss' graph. The fit of these points to the curve is excellent. (See Figure 4.)

To lend additional support to the correlation between the photometric distortion wave minimum and the emission-line maximum, the data of the present investigation indicate a pronounced maximum in the equivalent width of the K-line emission at phase 0.384. This point agrees extremely closely with the phase at which the distortion-wave minimum should occur in 1976-1977 (as extrapolated from Hall, Richardson, and Chambliss' curve). The point falls well within the ±0.1 phase unit uncertainty quoted by Hall, Richardson, and Chambliss (1976).

Table 4
PHASE OF AR Lac AT DISTORTION WAVE MINIMUM, EMISSION MAXIMUM, AND PERIOD CHANGE

Epoch[a] (year)	Phase of Distortion Wave Minimum[a]	Phase of Emission Maximum	Phase of Period Changes[a]
1926.5-1932.1	0.35		
1928.7-1929.6	0.25		
1928.8-1931.8	0.35		
1931.3-1931.8	0.30		
1932			.25 (decrease)
1938[b]	0.58[b]		
1939[b]	0.96[b]		
1938.5-1939.9	0.15		
1939.0-1941.0	0.20		
1938.9-1941.0	0.25		
1937.6-1955.4	0.10		
1940[b]	0.94[b]		
1946.5-1947.0	0.95		
1957			.75 (increase)
1960.5-1960.8	0.65		
1966			.25 (decrease)
1969.7-1970.8	0.15		
1968-1972[c]		0.15[c]	
1968.5-1969.0	0.98		
1972.8-1973.0	0.88		
1974 ±3-4 (predicted)			.75 (predicted increase)
1974.7[d]		0.47[d]	
1974.8-1975.0	0.72		
1975[e]			observed period decrease[e]
1976.9[g]		0.384[g]	
1979[f]	0.87-0.93[f]		

a Hall, Richardson, and Chambliss (1976) except where otherwise indicated
b Kron (1947)
c Babaev (1974c)
d Weiler (1978)
e Scarfe and Barlow (1978), not included in Figure 4 - no phase published
f Caton (1981)
g Hoffman, present investigation

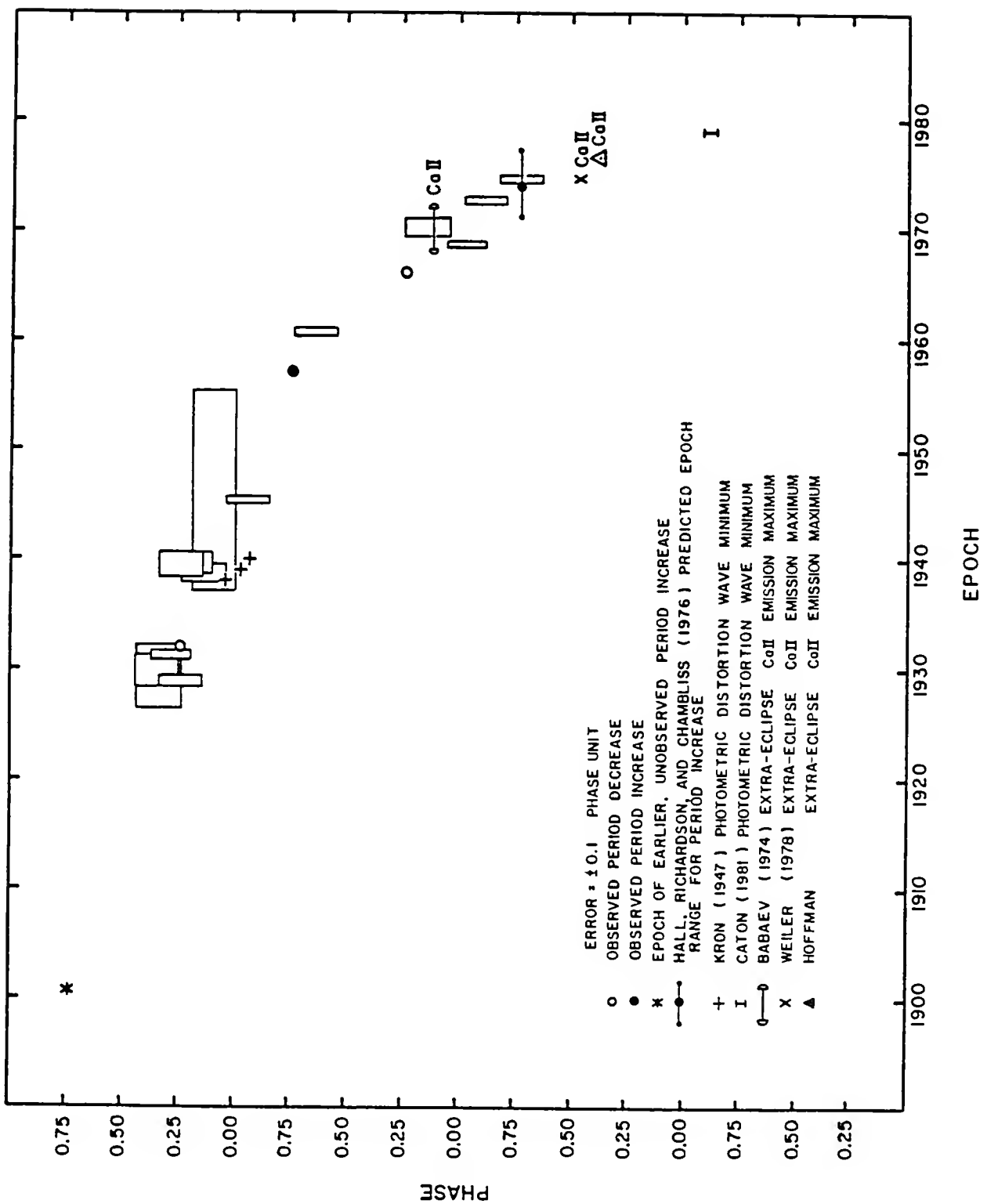
See Figure 4.

Figure 4
THE ENHANCED MIGRATION CURVE FOR AR Lac

The enhanced migration curve is a composite of three relations between the system (orbital) phase at which certain phenomena have occurred and the epoch (year) of occurrence.

The asterisk, the boxes, and the empty and filled circles form the original migration curve for AR Lac (Hall, Richardson, and Chambliss, 1976). This curve was constructed by plotting the system phase at which the minimum of the migrating photometric distortion wave has been observed versus epoch of observation. From the graph it can be seen that between 1900 and 1980, the distortion wave minimum has migrated in longitude through three complete migration cycles, or three times around the star, each sucessive cycle being completed in less time than the previous one. The migration cycle period has decreased from 45 to 15 years during the length of time that AR Lac has been observed. Also included on the original curve are the calculated (but not actually observed) system phases of the occurrence of the distortion wave minimum at which period changes have been observed as a function of epoch of observation. A relationship is therefore almost definitely demonstrated between distortion wave minimum and period changes; but, as indicated by the data, no simultaneous observations of both events have been made to verify the phase of the distortion wave minimum at the very epoch of a period change.

The additional points for the indicated observers were inserted by the author to construct the enhanced migration curve. The data of Kron and Caton represent the system phases at which the distortion wave minimum was observed at various epochs. The data of Babaev, Weiler, and Hoffman represent system phases at which apparent extra-eclipse Ca II emission maxima have been observed at various epochs. Coincidence of these three data points with the curve for the other two relations indicates a tenative relationship among all three phenomena, tenative because in only one instance--that of Babaev's data--is there an apparent phase concurrence of an observed (presumably) extra-eclipse Ca II emission mamimum with an observed distortion wave minimum during (presumably) the same epoch.


PHASE
EPOCH
0.75
0.50
0.25
0.00
0.75
0.50
0.25
0.00
0.75
0.50
0.25
0.00
0.75
0.50
0.25
1900
1910
1920
1930
1940
1950
1960
1970
1980
CaII
CaII
CaII
ERROR = ± 0.1 PHASE UNIT
OBSERVED PERIOD DECREASE
OBSERVED PERIOD INCREASE
EPOCH OF EARLIER, UNOBSERVED PERIOD INCREASE
HALL, RICHARDSON, AND CHAMBLISS (1976) PREDICTED EPOCH RANGE FOR PERIOD INCREASE
KRON (1947) PHOTOMETRIC DISTORTION WAVE MINIMUM
CATON (1981) PHOTOMETRIC DISTORTION WAVE MINIMUM
BABAEV (1974) EXTRA-ECLIPSE CaII EMISSION MAXIMUM
WEILER (1978) EXTRA-ECLIPSE CaII EMISSION MAXIMUM
HOFFMAN EXTRA-ECLIPSE CaII EMISSION MAXIMUM

It can be concluded tentatively, then, that in AR Lac there does exist a phase correlation between the minimum of the photometric distortion wave and the maximum of the extra-eclipse K-line emission.

Conclusion. Combination of the data obtained in the present investigation and in other investigations has indicated a possible relationship among the minimum of the photometric distortion wave, the period changes, and the maximum of the K-line emission in AR Lac: namely, that all three of these phenomena appear to lie along the same curve of phase of occurrence versus epoch. It appears that when the (dark) starspot region is facing earth (phases 0.25 and 0.75), energetic matter ejected from this region would produce not only period changes in the system but also a minimum in the photometric distortion wave and a maximum in the observed K-line emission.

Summary

Examination of the spectral plates of AR Lac and the graph of K-line emission intensity versus phase in this investigation indicates that the K-line emission of AR Lac is present throughout the cycle and is phase- and/or time-dependent, not random. The variations consist of two parts: the geometrical effects of eclipse and the physical effects of non-uniform emission over the surfaces of the components.On an absolute scale the emission is stronger at secondary mid-eclipse than at primary mid-eclipse.

The nature of the graphical relation between the K-line emission and phase indicates that there is emission generally produced over the entire surfaces (or at least in complete equatorial bands). There are also concentrations of emission in fixed regions at the tips of the tidal bulges of both stars. Further, there is (1) possibly some non-phase-dependent flare-like Ca II emission activity or (2) possibly a Ca II-emission region migrating in longitude and drifting in latitude.

The photometric and spectroscopic observations of others and the line-profile asymmetry of the present investigations confirm the presence of the surface emission and discrete concentrations of emission, but they do not establish any of the characteristics of the latter. The general distributed emission accounts for the observation of emission throughout the cycle; the tidal bulge emission areas account for the behavior in the vicinity of and within eclipse. Either the possible migrating source or the possible flare activity accounts for the observation of the extra-eclipse emission peak. The width of this peak is interpreted as the partial duration of visibility of the concentrated emission region, which is either an active area carried in and out of view by the rotation of the star or a flare which happened to occur at that phase.

Both components of AR Lac have deep convective envelopes and do not have dominant tidal bulges; therefore they appear to be good candidates for differential rotation and the solar model of spot drift toward the equator.

The pre- and post-primary eclipse decreases in emission are attributed to an increase in absorption due to a circum-secondary envelope, the presence of which is further supported by UBV photometric light-curve pre- and post-primary eclipse depressions, scatter in infrared light curves, ultraviolet and infrared excesses, and the symmetry of the H-alpha emission profile within and outside of secondary eclipse.

The phase of the minimum of the photometric distortion wave, the phase of the maximum of the K-line emission, and the phases of period changes apparently all follow the same curve when plotted as a function of phase versus epoch. The seeming contradiction of a period decrease at phase 0.72 in 1973-1976 is resolved by considering that the rapid migration of the wave during that period and the poor epoch-resolution of the observations probably blended an initial period increase and a slightly larger subsequent period decrease to produce the very small net period decrease reported during that time period.

The period increases and decreases coincide with the times at which the spotted area would be on the leading and following edges of the star, respectively. At these times the photometric distortion wave would be observed at minimum and the Ca II emission at maximum.

SECTION V
GENERAL MODEL

Introduction

In culmination of this investigation, models for AR Lac and interpretations of previous observations of AR Lac are presented, discussed, and augmented by the author. The results of the present investigation have been incorporated to form an integral part of these augmented models in order to synthesize a general comprehensive physical and evolutional model for the AR Lac system.

Explanations for H and K emission, other spectroscopic anomalies, and photometric variations began with models for the sun. These solar models were soon followed by a plethora of models for the many different types of stars and stellar systems which exhibit these characteristics.

Spectroscopic Characteristics

Ca II Emission

Many suggestions have been made for the site, size, mechanisms, and motion of the Ca II emission in the sun and other stars. Conclusions regarding the structure of these stars have been drawn by observing the behavior of Ca II in emission and absorption.

Site of the emission

Several widely differing stellar layers and surface positions have been proposed as the site of the Ca II

emission in the sun and other stars. It seems likely that the emission might not arise from the same site in all stars.

The chromosphere. Examination of the solar Ca II lines indicated to Deslandres (1894) that the emission arises in an ascending layer in the chromosphere.

Confirmation of the solar chromosphere as the site of the emission came from observations that the H and K emission cores of the solar disc "merge smoothly with the chromospheric emission bulge" (McMath et al., 1956, p.7) and that the line intensities of the disc and the bulge are similar. These data and observations showing that the K-line emission is enhanced over plages provided these observers with "convincing evidence" (McMath et al., 1956, p.7) that in the sun the Ca II emission arises in hot columns in the very low chromosphere.

Struve (1946) proposed that the emitting star in RW Ursae Majoris has an extended tenuous calcium chromosphere, tidally extended far beyond its photosphere. The emission would therefore be most apparent at phases 0.25 and 0.75.

Further evidence that the emission arises in the chromospheres of stars has been obtained by several investigators. Wilson and Bappu's (1957) data for the widths and the intensities of stellar H and K lines seemed to indicate that the emission is produced in an optically thin chromospheric layer. Wilson (1963) asserted that the intensity of the H and K emission "must almost certainly be

a measure of general chromospheric activity" (Wilson, 1963, p.833). He added that, in contrast, theories of earlier observers seemed "to imply that all stars of given mass and chemical composition should have equally strong reversals" (Wilson, 1963, p.832). In their model for achieving the best fit of observed Ca II line shapes with theoretical line shapes, Linsky and Avrett (1970) identified the emission site as being the lower chromosphere and further specified that the chromosphere must be optically thick at the line centers. Naftilan and Drake's (1977) calculations of the thickness of the Ca II emitting layer in the secondary of AR Lac yielded values compatible with what would be expected for a chromosphere. From the small differences generally observed between the radial velocities of the Ca II emission and the Ca II absorption in late-type binaries, Young and Koniges (1977) concluded that the emission originates "in a chromosphere which is rigidly attached to the star, and not in some gaseous stream extending between the component stars" (Young and Koniges, 1977, p.839). The observed rapid changes in the emission profiles over very short time intervals in AR Lac were interpreted by Naftilan and Drake (1977) as indicating that the components have very active chromospheres.

By application of this interpretation of intense Ca II emission as indicative of a chromospheric origin, the presence of the strong Ca II emission observed in AR Lac in the present investigation confirms the chromosphere as the layer of origination of the emission.

An extended envelope. When Joy (1941a,b) observed that the H and K emission lines in WW Draconis are displaced in the same direction as the absorption lines of the secondary, but exhibit a smaller range of displacement, he suggested that this characteristic could be explained by a model in which the secondary is surrounded by an envelope of emitting Ca II gas which has a pronounced tidal distortion in the direction of the primary. He offered support for his theory by further noting that the emission lines are weaker at secondary minimum, when a large part of this inter-component gas would be occulted by the primary.

Gas streams. Struve (1945) proffered the idea that Ca II emission lines in binary systems are produced primarily in inter-component gas streams detached from the components.

The tidal bulges. Observations of RZ Cancri by Hiltner (1946) revealed that the Ca II emission was absent during a portion of the partial phases before and after primary eclipse and during the entire totality of primary eclipse. Hiltner interpreted this behavior to mean that "the emission has its origin at both extremities of the elongated primary star" (Hiltner, 1946, p.166). From the localization of the emission observed in RZ Cnc and RW UMa Struve (1948) inferred that in AR Lac the emission is also "in a localized cloud at the extremities of the tidal bulges" (Struve, 1948, p.155) of the AR Lac secondary. After determining that differential gravitational acceleration over the surface of a rotating star would produce currents which might have

velocities great enough to generate emission lines Gratton (1950) concluded that "the currents are much stronger near the bulges, which may explain the localization of the observed emission" (Gratton, 1950, p.38).

The behavior of the emission in the present investigation indicates that the tips of the tidal bulges of both components of AR Lac are responsible for a part of the Ca II emission. (See Section IV.)

The entire stellar surface. Struve's (1952) observations of AR Lac caused him to reverse himself on his previous inference of the tidal bulges as the emission sites. His spectra verified that when the AR Lac secondary's Ca II absorption lines are narrow, its emission lines remain broad. From this circumstance Struve concluded that the emission lines originate either from the entire stellar surface or from complete equatorial zones rather than from localized areas on the tidal bulges. Further, for RS CVn, Weiler (1978) deemed the tidal bulge model "inadequate" because Catalano and Rodono (1969) were unable to confirm Hiltner's (1947) observation of the disappearance of the Ca II emission at secondary minimum. Oliver (1982) has also confirmed that the emission in RS CVn does not disappear during secondary eclipse.

The results of the present investigation indicate a source distributed across the entire diameter of each star to be one contributing component of the emission. (See Section IV.)

Patches. Struve (1945) indicated that the Ca II emission in binaries is occasionally produced in the atmospheres of the components, rather than always in gas streams. As evidence for this stand he offered the fact that the emission lines are often seen at great intensity at the midpoint of primary eclipse, when any inter-component gas streams would be occulted by the secondary. This observation suggested that the lines are produced not only in the sub-primary hemisphere of the secondary but also in its anti-primary hemisphere. The lack of observed broadening or doubling of the lines indicated that the emission-source size is not as large as the entire hemisphere of the secondary.

Struve's (1946) radial velocity measurements and observations of emission-intensity changes with phase in RW UMa induced him to conclude that the emitting region is dynamically attached to one of the components rather than being a detached feature. His calculations of the diminution of the emission-line intensity which would result from a uniformly distributed region of RW UMa undergoing eclipse yielded a value far less than what estimates based on his observations indicated would actually be observed. (He could not make the actual measurements because he had no plates during primary minimum.) From these calculations he deduced that in RW UMa the emitting source is a non-uniform distribution over the stellar surface.

Kron's (1950) studies of late-type dwarf stars with Ca II emission and non-uniformly luminous surfaces (surfaces with small brighter and fainter areas) led him to propose that the emission originates in these small areas. The broadening of the Ca II and other emission lines in Sanford's plates of AR Lac suggested to Kron (1952) that AR Lac's patchiness must extend over a large range of longitude in the equatorial region rather than being concentrated in isolated areas. Weiler (1978) observed an extremely large change in the Ca II emission level of AR Lac over a very short period of time between second contact and mid-secondary eclipse. He interpreted this rapid change as possibly indicating the eclipse of a "localized emission area" (Weiler, 1978, p. 88) on the secondary because the observation could not be explained in terms of the eclipse of an emitting area uniform over the surface of the secondary.

In the present investigation also, evidence points toward a concentrated region of emission on one AR Lac component as one of the sources of the observed emission. (See Section IV.)

Mechanism for and motion of the Ca II emission

One of the long-standing problems of Ca II emission has been the determination of the mechanism by which the emission is produced. Various mechanisms and motions, presenting both large- and small-scale views, some based purely on observations and others based entirely on

theoretical considerations, have been suggested as the Ca II emission agent.

No detailed measurements of the motions of the emission or of the overall structure of the Ca II line profiles were performed in this investigation; consequently no suggestions for emission agents are offered from this source. For completeness, however, a brief review of the conclusions of other researchers is presented. (See Linsky and Avrett, 1970, for a wealth of information on the solar Ca II lines and some information on stellar Ca II lines.)

Eruptive activity. Eberhard and Schwarzschild (1913) surmised that stellar H and K emission lines are probably produced by the same types of eruptive activity that produce the solar emission lines: namely, sunspots, flocculi, and prominences. Struve (1945) also concluded that the origin of the Ca II emission reversal may be similar to that in the sun. Similar conclusions were drawn by Struve (1945) and observers at the Yerkes and McDonald observatories (Yerkes, 1948).

Kron's (1950) investigations of late-type dwarf stars with Ca II emission and non-uniformly luminous surfaces led him to propose that the Ca II emission arises in these small areas by activity similar to that associated with sunspots.

Collisions and thermal gradients. The structure of the solar Ca II lines was interpreted as being indicative of vertical and horizontal (latitudinal) circulation of singly ionized calcium vapor in the chromosphere (Deslandres, 1894,

as reported by St. John, 1910). The measurements of both investigators indicated that the emission (K2) arises in an ascending layer, whereas the absorption (K3) arises in a descending layer. St. John (1910) further determined that the absorption wings (K1) are produced in a layer below the K2 layer. St. John proposed that the high energy of the rising emitting layer might be produced by a temperature increase resulting from the transformation of mechanical energy into heat, a process which would be precipitated by the loss of velocity in the opposing rising and falling layers.

Following along the same lines as St. John, McMath et al. (1956) explained the presence of low-excitation and high-excitation lines by re-proposing Giovanelli's (1949) model, which suggested that the chromosphere is structured with alternating hot and cool gas columns (these have been observed as chromospheric supergranulation: Linsky and Avrett, 1970; Abell, 1982). McMath et al. modified this model slightly by adding cool overlying patches. Observations that K-line emission is enhanced over plages led to the conclusion that the emission (K2) arises in the hot columns. They surmised that the absorption core (K3) is produced by the emission passing through the cool overlying regions. Persistence to the limb of asymmetry in the emission profile ruled out St. John's (1910) interpretation that the asymmetry is caused by the rising and falling of the hotter and cooler columns, respectively. Instead,

the speculation was raised that the origin of the asymmetry might be the expansion of optically thick, rising hot gases.

From calculations of differences in gravitational acceleration over the surface of zeta Andromedae, Gratton (1950) determined that the resulting velocity of the currents expected in a rotating star "might be large enough to cause the local inversion of the thermal gradient which is required for explaining the [Ca II] emission lines" (Gratton, 1950, p.38).

Wilson and Bappu's (1957) data for the widths and the intensities of stellar H and K lines produced a theory somewhat reminiscent of the solar theories of St. John (1910) and McMath et al. (1956). Wilson and Bappu's data seemed to indicate a picture similar to what is seen in the sun namely, that the H and K lines are of nearly equal width and of intensity ratio 1:2. This result is in accord with Doppler broadening by turbulence in an optically thin chromospheric layer, rather than with abundance broadening (a pure damping profile) at large optical thickness. (They noted that Goldberg, however, had indicated that it might be possible to explain the broadening by abundance in an optically thick layer.) These results led Wilson and Bappu to offer the following extremely tentative model to explain both the emission-producing mechanism and the functional dependence of Ca II emission-line width upon luminosity in late-type stars. They proposed that in all late-type stars an outward flow of material would travel to the height of

the lower chromosphere, where laminar flow would become turbulent. The mean spread of the turbulent velocity would be a function of the flow velocity, which would in turn be a function of luminosity alone. In the layer of turbulence, kinetic energy of flow would be transformed into heat, which would be absorbed to increase thermal excitation; and this excitation would in part be responsible for the line emission. The turbulence would reduce the original outward flow velocity to a slow outward drift. Above the emitting region would lie a cooler absorbing region of material slowly falling inward. (On a similar theme Sanford, 1951, had suggested that the difference between the radial velocities of the Ca II absorption and emission in AR Lac could possibly result from outward flow of the emission source relative to the absorption source. He had reasoned further that the absorption-line shallowness and width, which is uncharacteristic of stars of such late spectral types, is produced by rotational broadening in components rotating synchronously with the revolution period of the system.)

In further concurrence with the idea of collisions of opposing intrastellar streams of matter are the observations of the Cepheid-like variable BL Her (Lick, 1966). Hydrogen and Ca II emission lines were observed during the rising portion of the light curve, the emission and the atmospheric velocity reversal occurring during a stillstand on the light curve, when collisions of layers of material would be maximal.

Linsky and Avrett (1970), on the other hand, concluded that the H and K line profiles and the existence of the emission are "direct consequences" of (1) a rise in temperature in the lower chromosphere, (2) line formation by the mechanism of non-coherent scattering, (3) a chromosphere which is optically thick at the line centers, and (4) non-thermal broadening which increases with height.

Goldberg (1964) surmised that the observed large variations in emission width over the surface of the sun and among stars would probably be caused by chromospheric density gradients and temperature gradients in strata above the emitting level.

Acoustic energy flux, the commonly assumed heating source for chromospheres, was investigated by Young and Koniges (1977). They determined that both the strength of chromospheric emission and the strength of tidal coupling are directly related to the ratio of the radius of a binary component to its Roche lobe. Stronger tidal coupling would therefore imply stronger chromospheric emission. Expansion of one of the stars as it evolves would further enhance the effect of tidal coupling. Combination of this result with Linsky and Avrett's (1970) argument that strong Ca II emission is indicative of a large chromospheric temperature gradient and with Stein and Leibacher's (1974) theory of chromospheric heating by acoustic energy transport (with the photosphere acting as a low-pass filter) evoked the suggestion that tidal coupling may enhance the chromospheric

heating tremendously by increasing the density scale-heights. This activity would shift the acoustic spectrum toward lower frequencies (the low-frequency cutoff limit varies inversely as the scale height) and result in much greater dissipation of acoustic energy in the chromosphere. The resulting enormous increase in the temperature of the chromosphere would produce the observed Ca II emission. (See Blanco et al., 1974, for results for main-sequence stars.)

Thermal effects were echoed by Hall (1976), who inferred that "the extreme degree of the chromospheric activity and spottedness might mean that the affected stars are thermally unstable" (Hall, 1976, p.46).

On an atomic level Struve (1946) argued that in binaries the Ca II emission arises in part by the mechanism of ordinary resonance scattering (normal radiative excitation). He emphasized that the emission mechanism is not fluorescence or any of the unusual means of line formation known to occur in some regions of the sun or thought to occur in some stars. Struve (1948), however, recanted his earlier pronouncement by contending that in AR Lac the emission mechanism is fluorescence.

Gas streams. Swings and Struve (1952) summarized Struve's previous conclusion that "all close binaries are associated with gaseous streams of a nature resembling whirlpools. These streams produce emission and absorption lines which are superposed over the normal stellar spectra

of the two components" (Swings and Struve, 1952, p. 412). Babaev (1974c) suggested that the variation of the H and K emission throughout the orbital cycle of AR Lac may be due to gas streaming.

Binary character. A quite different mechanism was offered by Swings and Struve (1941), whose observations of late-type systems with Ca II emission suggested that the very fact that these stars are binary rather than single may be the underlying cause of the emission. They stated that "binary character stimulates the formation of emitting shells or layers" (Swings and Struve, 1941, p.245). Observations in support of this hypothesis were made by Wilson (1963), who observed two main-sequence visual binary systems (ADS 2644 and ADS 1889), each with a spectroscopic binary companion. The spectroscopic binary in each visual system exhibited much stronger Ca II emission than its single visual companion, a circumstance which induced Wilson to speculate rather tentatively regarding close binaries, "excessive H and K emission is stimulated either because of their relatively rapid rotation or in some other manner by the nearness of the companion star" (Wilson, 1963, p.835). He indicated, however, that rotation could not be the only factor because one single star in another visual binary (ADS 14270 A) exhibited an amount of rotational broadening similar to that in the two spectroscopic binaries; but the strength of the emission in this rapidly rotating single star was no greater than in its companion, ADS 14270 B.

From the observation that stars of the same spectral type in visual binaries and in open clusters have similar emission strengths Wilson concluded that the emission intensity results from a kind of "genetic factor" (Wilson, 1963, p.838) traceable to the past history of the star: viz., its present age and the circumstances of its birth. A similar viewpoint regarding the effect of duplicity was expressed by Popper and Ulrich (1977) when they noted that the basis for differences in the behavior of single K0 IV stars and the K0 IV stars in the RS CVn systems undoubtedly lies in the binary nature of the latter. Binariness would affect rotation rate, magnetic field, and gravitational potential (Popper and Ulrich, 1977) and would generate tidal coupling (Young and Koniges, 1977).

Conclusion. It would seem likely that the binary nature of AR Lac, the other RS CVn systems, and, in fact, all close pairs would tend to excite or enhance behavior such as the following, which would in turn produce the observed Ca II emission: (1) eruptive activity, (2) surface currents and vortices (which would induce collisions of material and inversion of thermal gradients), and (3) chromospheric heating by acoustic energy transport.

On the atomic level the line-forming mechanism which seems best able to account for the core emission is non-coherent scattering in an optically thick chromosphere. The emission cores are Doppler-broadened predominantly by turbulence rather than thermally.

Depressions in emission

Pre- and post-primary-eclipse depressions in the Ca II emission observed in the present investigation were attributed to an increase in absorption due to the presence of a circum-secondary envelope. This conclusion was the option left when it was determined that these net decreases in emission could not be explained by an actual decrease in the emission activity and be consistent with the three-part emission model. (See Section IV.) There is both spectroscopic and photometric evidence of such an envelope. (See Section V: Stage of Evolution.)

Magnetic fields

Wilson (1963) inferred from studies of the sun that there could also be in some other stars a strong correlation between the local chromospheric magnetic field strength and the intensity of the Ca II emission.

Observations of the sun revealed that the solar H and K emission-line flux is higher in plages than in the quiet chromosphere. In the main-sequence stars examined by Blanco et al. (1974), the H and K emission-line fluxes were similar in magnitude to plage fluxes, a correlation from which the presence of magnetic fields in stars with H and K emission was indirectly inferred.

Adhering to the theory that magnetic fields protruding through the surface of a star produce starspots, Mullan (1974) suggested that tidal effects in binary systems might enhance the breakthrough effect, much as the alignment of

Venus, Earth, and Jupiter raises substantial (600-km) tides which could trigger activity tides on the sun. (The idea may have merit for close binaries; but Smith, 1983, states that planet-raised solar tides of any magnitude are "a fable" reminiscent of the "Jupiter Effect.") The magnetic fields would be generated and maintained by dynamos produced by fast differential rotation in a deep convective zone, exactly the situation which exists in AR Lac. The presence of spots is therefore indicative of magnetic fields in AR Lac.

There have apparently been no measurements of the Zeeman effect undertaken for RS CVn stars in order to attempt to confirm by direct observation the presence of such magnetic fields.

Other Spectroscopic Features

A number of salient spectroscopic features besides Ca II emission are exhibited by stars with Ca II emission lines. From these spectral characteristics a variety of conclusions regarding the nature of these stars have been drawn. A very brief mention of these spectroscopic features is included, again for the sake of completeness.

Hydrogen, cerium, iron, and other metals

Struve (1945) and McMath et al. (1956) attacked the problem of the origin of hydrogen emission. Sanford (1951) and Struve (1952) sought to explain the phase-variability of lines of iron and cerium in AR Lac. Included in their respective theoretical pictures were (1) atmospheric heating

by bombardment by intercomponent or circum-component particles and (2) on the sub-primary face of the secondary a large spot of turbulent gases which would be the site of prominence activity.

Radio emission

From observations of radio emission and a large radio flare in AR Lac (Hjellming and Blankenship, 1973; Gibson and Hjellming, 1974), Naftilan and Drake (1977) concluded that the radio emission mechanism in AR Lac is unlikely to be thermal bremsstrahlung from circumstellar material because of (1) the flatness of the radio spectrum and (2) the rapid increase of the radio flux during the flare, and because (3) the size of the emitting region would be so large that it would engulf the entire system, and not merely be circumstellar about the secondary, as was suggested by Atkins and Hall (1972) and Milone (1976a,b).

Because the radio spectra of AR Lac are evocative of strong solar microwave bursts (which are generally considered to be synchrotron radiation), Owen and Spangler (1977) concurred with other observers that magneto-bremsstrahlung from "mildly" relativistic electrons (as often seen in solar flares) is the most probably radiation mechanism. That there was no clearly defined eclipse of the radio emission indicated that the source volume is much larger than the stellar components.

Photometric characteristics

Introduction

Many single stars and binary stars with Ca II emission exhibit light curve behavior such as irregular light variations and variation of light level with rotation. Many eclipsing binaries exhibit such characteristics as asymmetry of eclipses and migration of a quasi-sinusoidal wave-like distortion (the photometric distortion wave in RS CVn stars). Various mechanisms have been proposed to explain these anomalies.

Depressions in the Light Curve

Hall (1976) interpreted Catalano's (1973) observation of an approximate 0.05-mag depression in the light curve of AR Lac just prior to first contact and just after fourth contact of primary minimum to be caused by the eclipse of the primary by an envelope or shell of material surrounding and possibly filling the Roche lobe of the secondary. This enveloping structure would result from mass ejection from the brighter hemisphere of the secondary. These pre- and post-primary eclipse depressions were explained similarly by Rhombs and Fix (1977), who suggested that the optical thickness of the material in a circumstellar high-temperature gas flowing outward from the cool component would be sufficient to produce the depressions.

Irregular Light-Curve Variations and the Photometric Distortion Wave

Wood (1946) inferred from light-curve variations which occurred only outside of primary minimum that the AR Lac

primary is intrinsically variable. Babaev (1971) and Chambliss (1976) confirmed the presence of irregular photometric variations in AR Lac. Chambliss concluded that the surface luminance of the secondary is more uniform than that of the primary. His observation that primary minimum is much less distorted than secondary minimum substantiated earlier conclusions that the intrinsic variability of the system can be attributed primarily to the primary.

Wood (1946) eliminated pulsation as the agent causing the intrinsic variation of the AR Lac primary, concluding that the period of the observed variations would have to be on the order of only a few hours, much shorter than that actually observed.

These variations could be a part of the photometric distortion wave; or, alternatively, they might be small flares.

Caton (1981) concluded that any irregularities observed in the light curves during eclipses of RS CVn stars must be caused by some type of low-level flaring.

Several agents such as pulsation, a ring or shell of material, gas streams, and starspots, have been proposed as being responsible for producing the migrating quasi-sinusoidal wave-like distortion in the light curves of the RS CVn systems. Various arguments pro and con regarding these suggested models have been presented.

Pulsation as the agent

Being unable to explain by either the ellipticity effect or the reflection effect the periodic phase-persistent distortion of the light curve of RS CVn, Popper (1961) proposed the cause to be an orbital-period-synchronous pulsation of the cooler star. Distortions not persistent with phase would have a different origin, such as Kron's "patches."

Chambliss (1976), however, concurring with Wood (1946), ruled out pulsation as the cause of the intrinsic variability of AR Lac because the theoretical pulsation constant for Population I variables yields pulsation periods much shorter than the time scale of the observed variations.

Ring, shell, or envelope as the agent

First proposed in 1967, a model to explain the migrating photometric distortion wave in RS CVn was revived by Catalano and Rodono (1974). They suggested that the primary is surrounded by an extended, non-uniformly distributed, absorbing equatorial ring which is tilted relative to the orbital plane. Changes in the projected area of this ring on the primary as a function of phase would cause the photometric distortion wave in the light curve outside eclipse. Precession of the rotation axis of the primary would produce the retrograde migration of the wave in successive cycles. Regarding this tilted ring model, Oliver (1975) offered several arguments which cast severe doubt on its validity. He enumerated kinematical and

photometric reasons that the existence of such a ring would be highly improbable, among them the apparent lack of a mechanism for the formation of the ring, the rapid loss of non-uniformity which would occur in such a situation, and the difficulty in explaining the blueing of the light at photometric distortion minimum if the ring surrounds the primary rather than the secondary. He also cited the fact that there existed no spectroscopic evidence for an absorbing ring.

Gas streams as the agent

A reanalysis of all the data from previous light curves of AR Lac was performed by Theokas (1977). He made application of Kopal's (1959) suggestion that a shock wave created by hypersonic gas streams from the secondary impinging on the atmosphere of the primary would produce a bright spot on the primary. He therefore arrived at the conclusion that the asymmetry in the light curve of AR Lac is produced by "light spots," in contrast to Hall's (1972) dark spots. (See Starspots as the agent.) Support for the idea was evinced by Batten (1973), who demonstrated that for short-period binaries, streams are more likely to be prominent than discs or clouds.

Starspots as the agent

Observations of "small abrupt irregularities" (Kron, 1947, p.264) in the light level of AR Lac during primary ingress and egress prompted Kron (1947) to interpret these changes by following in the footsteps (perhaps unbeknownst

to him) of many nineteenth-century astronomers. His predecessors had ascribed light changes in some variable stars to the existence of surface spots which are alternately visible and hidden as the star rotates (Russell, 1906). Kron described the phenomenon as "huge light and dark patches" (Kron, 1947, p.264) which he observed being eclipsed and re-emerging during the partial phases of primary minimum, thereby producing "steps" (Kron, 1947, p.264) in the shoulders of his eclipse curves. His photometric data indicated that at least 20% of one hemisphere of the primary is covered by patches and that the size of an individual patch is 3-5% of the hemispheric area. Observations over several cycles of the system showed that the light-curve irregularities caused by the patches repeated themselves in consecutive cycles, thereby indicating that the patches disappear and reappear around the limb as the star rotates. Over longer periods of time, though, the character of the light variations changed, indicating that the patchy areas move across the surface of the star and that they "form and dissolve" (Kron, 1947, p.264). Regarding Kron's hypothesis that the AR Lac primary is covered with large areas of differing luminances, Struve (1952) deemed it reasonable to suppose that the secondary might also be "patchy" (Struve, 1952, p. 22).

Through the use of starspot models, however, Caton (1981) determined that short-time variations in light level in or out of eclipse (e.g. Kron's "steps" during primary

eclipse) would not be caused by spots. Photometric variations due to the presence of spots would be gradual rather than abrupt. The occultation and reappearance of spots during eclipse would therefore have no significant effect on the light curve within eclipse. Spots visible on the stellar disc outside eclipse would, however, cause a gradual fall (the photometric distortion wave) in the extraeclipse light level. "This strongly suggests that any activity observed during an eclipse of an RS CVn system must be some type of low-level flare activity, rather than any kind of geometrical effect related to spots" (Caton, 1981, p.68). (See Existence and observability of starspots.)

While analyzing four systems (AR Lac, RT And, RS CVn, YY Gem) with light-curve distortions, Kron (1952) interpreted the periodicity of the distortions with the rotation to be clear evidence that the distortions are produced by the rotation. In the light curve of YY Gem he noted that the distortions outside eclipse could not be explained by tidal effects or by the reflection effect because of the asymmetry of the extra-eclipse light curve. During primary eclipse the character of the distortions took on the form of large-amplitude high harmonics of the rotation period. Such harmonics would be generated only by the eclipse of a spotted region during rotation (Russell, 1906), and not by the mere presence of a spotted area on the surface of the rotating star. Outside eclipse no such harmonics in the distortions were observed. Because of the asymmetry of the

extra-eclipse light curve, the distortions outside eclipse could not be explained by tidal effects or by the reflection effect. Because the presence of the harmonics indicated that the source of the distortions undergoes eclipse, Kron concluded that this source must be either on the surface of the star being eclipsed or between the two stars. He favored the former alternative because material between the two stars would be of a density insufficient to emit enough energy to be observed by broad-band photometry. He demonstrated that in YY Gem the distortions in and out of eclipse could be explained by variations in light which would result from foreshortening, rotation around the limb,and eclipse of non-uniformly luminous areas on a patchy model, as in AR Lac.

Enlarging upon Kron's basic idea, Hall (1972) devised a more detailed model to explain the photometric anomalies of the RS CVn group. He proposed that the migrating distortion wave and the inconsistencies in the minima could be explained by a stellar "sunspot cycle" incorporating an equatorially centered band of large dark areas (Oliver's suggestion to Hall) 60 degrees wide in latitude and 180 degrees long in longitude. The band would drift in latitude and move with differential rotation (Marks' suggestion to Hall) as the cycle progresses. (Although in close binaries it is usually considered that the stars rotate synchronously with the orbital period, Hall abandoned the idea of strict synchronous rotation, reasoning that it would be expected

that a star in a binary system would exhibit differential rotation as long as the tidal bulge raised by its companion does not override the natural tendency of the star to rotate differentially.) For stars with radiative envelopes the rotation is faster at the poles than at the equator. For stars with convective envelopes no theory has been formulated (apparently still to date); however, the sun serves as an example: the rotation is faster at the equator than at the poles. The cooler star in RS CVn is cool enough to have a deep convective envelope (Popper, 1961). Estimates of the gravity-brightening index of the AR Lac system indicate that both components have deep convective envelopes (Chambliss, 1976). Even on a differentially rotating star, however, there would be one latitude, the "corotating latitude" (Hall, 1976, p.325), which would rotate synchronously with the system. No theory or observational procedure has been developed for the determination of the corotating latitude.

If the starspots are rotating faster than the corotating latitude (i.e., if they lie on the equatorward rather than the poleward side of the corotating latitude), the migration of the spots (and the distortion wave) would be retrograde. The rate of migration would increase as the latitude of the spots decreases, the maximum migration rate occurring when the spots are the farthest from the corotating latitude (and closest to the equator). When the spots make the discontinuous transition from the maximum

retrograde migration rate (when farthest from the corotating latitude) to the minimum retrograde migration rate (when closest to the corotating latitude), the photometric distortion wave would be at a minimum; and the Ca II emission would be at a maximum (Weiler, 1975, 1978). (Weiler reasoned that the coincidence of the phase of the maximum of emission intensity with the phase of the minimum of the photometric distortion wave in three RS CVn systems (UX Ari, RS CVn, Z Her) is, by analogy with the sun, consistent with Hall's (1972) spotted-hemisphere-active- chromosphere model. Weiler based his argument on the fact that solar H and K emission is associated with sunspot regions and an active chromosphere.) The changing latitude of the spots on the star would therefore be manifested by a change in both the migration rate and the amplitude of the distortion wave. This behavior is similar to what occurs during the sunspot cycle as depicted in the solar "butterfly diagram" (Hall and Henry, 1978), but this analogy with the sun is valid regarding spot position and migration rate only, not amplitude of wave. When a sunspot cycle ends, the spots are at the lowest latitudes and are at maximum rate of "migration" in longitude; but, simultaneously, when the sunspots make the discontinuous transition from the lowest latitudes to the highest latitudes (and from the maximum to the minimum longitudinal "migration" rate), the "solar distortion wave" is at a maximum, not at a minimum.

During a sunspot cycle the change in the amplitude of the "solar distortion wave" is observed to be produced by the continually changing number of spots on the solar surface. From cycle to cycle in the sun, the amplitude of the solar distortion wave minimum (which occurs at the maximum number of sunspots) also changes. Presumably, during a given starspot cycle and from cycle to cycle the sizes and numbers of spots would vary also, as in the sun, thereby producing (1) the observed continual changes in the amplitude of the photometric distortion wave and its ostensibly accompanying Ca II emission over one cycle and (2) the variations in the minima and maxima of both phenomena from cycle to cycle. These occurrences would perhaps render both phenomena virtually unobservable during some portions of a spot cycle, or even over several epochs during a long interval of very few spots. (Along these lines Oliver (1971, 1974) suggested that the common origin of the distortion wave and the Ca II emission [and their consequently coupled behavior in amplitude change] might resolve the controversy regarding the reported disappearance versus non-disappearance of the emission during secondary eclipse of RS CVn.) Further, Weiler's (1978) observation of basically random variations of the Ca II emission in AR Lac and Caton's (1981) observation that the amplitude of the AR Lac distortion wave was extremely low in 1979 support this suggestion. Apparently no theory presently exists upon

which to base sizes or numbers of starspots during a starspot cycle or from cycle to cycle. Further, no detailed study of the changes in the amplitude of the distortion wave in RS CVn stars has been completed in order to determine whether the changes in the number of spots follow a latitude-amplitude and cycle-to-cycle pattern mirroring that of the sun. Changes in the migration rate in RS CVn (Hall, 1972, from the data of Catalano and Rodono, 1967, 1969) and in AR Lac (Hall, Richardson, and Chambliss, 1976) have been correlated with distortion wave minima.

In the model described above the spots always remain on the equatorward side of the corotating latitude; therefore the photometric distortion wave would be observed to always migrate retrograde. Several RS CVn systems (UX Ari, SS Cam, RS CVn, UX Com, WW Dra, Z Her, PW Her, GK Hya, RT Lac, AR Lac, RV Lib, SZ Psc, TY Pyx, RW UMa: Hall, 1976) exhibit retrograde migration of the wave.

In contrast, two RS CVn systems (SS Boo: Hall and Henry, 1978; and V711 Tau: Chambliss and Detterline, 1979) exhibit direct migration of the wave. In SS Boo the migration was observed to reverse itself from retrograde to direct. Hall and Henry (1978) explained this reversal by an extension of Hall's spot model and modeled the starspot cycle (the cycle of migration and drift) after the solar "butterfly diagram." While the starspots are rotating faster than the corotating latitude (and their latitude is lower than the corotating latitude), they would behave as

described in the retrograde model. When the spots make the discontinuous transition from maximum retrograde migration rate (when they are farthest from the corotating latitude and closest to the equator) to direct migration (when they are at a higher latitude than the corotating latitude and rotating more slowly than the corotating latitude), the photometric distortion wave would be at a minimum; and the Ca II emission would be at a maximum (Weiler, 1975, 1978). The direct migration rate would be at its maximum as soon as the transition occurs because the spots would then be at their highest latitude, their farthest poleward of the corotating latitude. As the spots of the new cycle then begin their drift toward the equator, they would exhibit a slowing of the direct migration rate to a minimum (of zero) when they cross the corotating latitude. The migration would then revert to retrograde and increase from a rate of zero (at the corotating latitude) to a maximum. In this model the spots drift back and forth across the corotating latitude.

The "starspot cycle" model could be further extended to a third case, one in which the spots always remain on the poleward side of the corotating latitude. The migration would then always be direct because the spotted area would always be rotating more slowly than the corotating latitude. When the spots make the transition from the minimum direct migration rate (when they are closest to the corotating latitude and to the equator) to the maximum

direct migration rate (when they are farthest from the corotating latitude and the equator), the photometric distortion wave would be at a minimum, and the Ca II emission would be at a maximum.

Because the starspot cycles for the RS CVn stars may be quite long (23.5 years for RS CVn: Hall, 1972; and a smoothly decreasing 45-15 years from 1900-1980 for AR Lac: Hall, Richardson, and Chambliss, 1975), many years of observation may be needed to establish the migration-and-drift category to which each system belongs. AR Lac does, however, obey the relation Hall (1976) established for the period of migration: $(O - C) \simeq P_{migr}^2$, which allows a calculation of P_{migr} in advance of actual observation. The length of the starspot cycle for stars in each category could be determined by measuring (1) the time interval between the maximum and minimum duration of visibility of the Ca II emission, (2) the time interval between the maximum and minimum migration rates of the photometric distortion wave, and (3) the time interval between the absolute minima of the photometric distortion wave. Measurements of the phase-interval of visibility of the emission would provide a measure of the rate of differential rotation and the range of differential rotation, just as measurements of sunspot motions perform this function in the sun.

If the proposed spatial model for Ca II emission activity in AR Lac from 1968-1977 is indeed the case (see Section IV), the picture presented by this model would

integrate well with Hall's (Hall, 1972; Hall and Henry, 1978) model for the starspot cycle in RS CVn stars. The spatial model would allow a diminution of the duration of the visibility of the Ca II emission to be interpreted as the drift of the Ca II emission region to lower latitudes, with an accompanying increase in the migration rate of the distortion wave. An ever more rapidly increasing migration rate would signal the approaching end of of a starspot cycle, as perhaps would a decrease in the distortion wave amplitude, the latter phenomenon indicating a decrease in spot number and/or size, as observed in the sun as a sunspot cycle terminates. Both of these effects have been observed recently in AR Lac. Hall, Richardson, and Chambliss (1976) noted that the retrograde migration rate of the distortion wave in AR Lac is increasing, the rate of increase being quite rapid over recent years. Caton (1981) observed that the amplitude of the distortion wave was very low (less than 0.01 mag) in 1979. As a result of these observations, the author predicts that the distortion wave in AR Lac will soon (1) reverse its migration from retrograde to direct and/or (2) exhibit a discontinuous change in its rate of migration--to a much slower rate, which will again either (1) increase or (2) decrease and then increase, depending upon on which side of the corotating latitude the spots of the new cycle begin appearing.

The foregoing picture assumes that the drift is driven by a pole-equator temperature differential and that the

equatorward drift (i.e., as in the solar sense) of the spots is caused by the poles' being hotter than the equator (Mullan, 1974). If the poles were cooler than the equator, the drift would be poleward, as is indicated to be the case for the spotted flare star CC Eri (Bopp and Evans, 1973, as reported by Mullan, 1974).

Mullan (1974) hypothesized that starspots are convection cells which extend throughout a star's convection zone and that the deeper the convection zone, the larger the spot sizes. (Measures of the depth of the convection zone would therefore provide a means of ascertaining the sizes of starspots.) The drift category of a system might therefore be indicative of the internal structure (depth of convective zone and consequently, spot size) of the spotted component(s) of a system or of its/their evolutional stage.

Mullan (1974) suggested that in stars which have convective shells or envelopes rather than being convective throughout the entire stellar radius, spots would exist at latitudes away from the polar regions. Stars of this description could fall into any of the three migration-drift classifications, depending upon the latitude of the corotating region. Mullan determined that in these stars the variations in brightness produced by the rotation of the spots across the stellar disc would be periodic, the variations of greatest amplitude being observed in stars which are <u>almost</u> completely convective. It is assumed that the Ca II emission would follow the same pattern of

variation. The components of AR Lac are stars with deep convective envelopes (Chambliss, 1976); therefore they would be placed in the convective shell category, a classification which is confirmed by the periodicity of the photometric variations and the Ca II emission variations. The starspots of AR Lac would be rather large, because starspot size varies directly as the depth of the convection zone (Mullan, 1974).

Mullan suggested that in completely convective stars, on the other hand, the multipolarity of the stellar magnetic field might be such that the starspots would be confined to the polar regions. Mullan indicated that this situation would produce no periodic variation in the brightness of the star; instead there would be only non-periodic changes in brightness as the spots formed and decayed. Presumably the Ca II emission would reflect the same non-periodic irregularity. It might be concluded that in this case spot migration would fall into the category of direct migration only, the spots always being poleward of the corotating latitude. For a completely convective star the spots would be extremely large because the convection zone would be very deep.

Perhaps there is some evolution of the stars from one migration-type and spot-location classification to another. For example, the evolution might begin with completely convective stars (having very large, pole-confined spots, irregular light variations, and direct migration), proceed

through a stage with a deep convective shell (characterized by intermediate-latitude, slightly smaller spots, periodic light variations of slow migration rate, and alternating direct-retrograde migration), and finally end in a stage with a thin convective zone (with small spots close to the equator, periodic light variations of fast migration, and retrograde migration). On the other hand, such categories might not be evolutional, but instead be determined by some non-variable (or nearly so) characteristic of the star or the system (e.g., mass, size, differential rotation rate, separation, or period).

Existence and observability of starspots. The existence of starspots (small faint or bright photometric areas and/or Ca II emission areas) has been strongly indicated in many stars, the sun being the only star on which the phenomenon is visually observed.

The migrating photometric distortion wave in AR Lac certainly provides evidence of the existence of large groups of differentially rotating spots (Hall, Richardson, and Chambliss, 1976).

Migrating starspots were indicated to Kron (1947) by his photometric observations of "steps" in his light curve and their night-to-night shift in phase on the shoulders of primary minimum ingress and egress of AR Lac. He contended that the steps were generated by individual spots ("patches") being occulted and reappearing, and that the overall degradation of the shoulders and its shift in phase

was indicative of a group of spots in migration. Caton (1981), on the other hand, concluded that detection of individual starspots and the measurement of their sizes by observing for irregularities in the light curve of the partial phases of eclipse would be unlikely. His conclusion was based on the determination of the theoretical observability of starspots in RS CVn by construction of a theoretical light curve by constraining the inter-relationship of the spot temperature and size so that the spot flux remained constant and produced the observed photometric distortion wave and depth of secondary eclipse. The only irregularities exhibited by his theoretical curves were on the order of a few ten-thousandths of a magnitude, values which he concluded were one order of magnitude too small to be observable even by the best earth-based telescopes. He then strongly suggested that any irregularities observed during the partial phases of eclipses must therefore be produced by low-level flaring rather than individual spots. The entire group of spots could, however, be observed when they are all together on the earthward surface of the star--the group generates the photometric distortion wave. The discrepancy between Kron and Caton could have at least two bases: (1) Each person was observing a different star with different characteristics (AR Lac and RS CVn, respectively), and (2) each star could have been at a different level of activity, with numbers and sizes of spots sufficiently different to produce

the contradictory results. Further, Kron's probable error for a single normal point was approximately 0.001 mag, precise enough to allow him to easily observe the individual departures of the "steps" from his normalized light curves--the "steps" were typically depressed 0.01-0.05 mag below Kron's smooth normal curves, two orders of magnitude greater than Caton's required minimum for detectability. Neither the shape of Kron's "steps" nor their pattern of phase shift from night to night or epoch to epoch has the appearance of random scatter or random events (such as flares). The phase of the leading depression in each group regressed smoothly from about phase 0.06 in 1938 to about phase 0.94 in 1940. Although Kron's 1938-1940 observations (Kron, 1947) were not included in Hall, Richardson, and Chambliss' (1976) analysis of the migration of the distortion wave of AR Lac, the phase shifts cited above do lie in the same region of the migration curve for AR Lac as the observations used to define that curve during that same time interval (those of Gainullin, 1943; Wood, 1946; and Ischenko, 1963--see Figure 4). Kron therefore undoubtedly observed the distortion wave in AR Lac nearly 30 years before its presence was announced and apparently also observed large individual spots.

Detectability of large individual spots would then provide a means whereby the depth of the convective zone could be measured: the larger the spots, the deeper the zone (Mullan, 1974). Values obtained by this method could then be compared to those indicated by surface temperature

(Popper, 1961) and by gravity-brightening index (Chambliss, 1976).

The observations of peaks of Ca II emission in AR Lac by Babaev (1974c), Weiler (1978), and in the present investigation also speak strongly in favor of starspots, or isolated Ca II emission areas. The asymmetry of the Ca II line profiles in the present investigation further indicates a non-uniformity of light over the stellar disc (Huang and Struve, 1960).

A final piece of evidence for the existence and observability of starspots is the observation of fluctuations in the light curve of HD 206860 (Blanco, Catalano, and Marilli, 1978). The light variations of this single star, unencumbered by the presence of a companion, could be interpreted only as starspots because these changes occurred periodically with the rotation of the star.

Conclusion

The starspot model provides the most self-consistent explanation for the migrating photometric distortion wave, and there is much observational evidence in its favor. Pulsation and a tilted ring are clearly ruled out.

Period Changes

Introduction

Many systems, AR Lac included, have been observed to undergo abrupt period changes. Very large O - C values indicate that the period used in calculating the orbit of a system differs considerably from the period of that system

at the epoch of the observations. Several explanations have been offered for these period changes.

Mass Loss as the Mechanism

Following up on his discovery that AR Lac exhibited a sudden period change, Wood (1950) offered as possible explanations for such behavior in binaries: (1) faster-than-synchronous rotation of the fainter component, a process which would increase its tendency toward rotational instability, which would in turn increase its tendency toward mass loss (however, such non-synchronous rotation had not then and has not now been detected in AR Lac), or (2) eruptive prominences (similar to those on the sun) by which large amounts of material escape from the star by being explosively ejected beyond the Jacobi limiting surface. The direction of ejection of the mass would determine whether the period change is an increase or a decrease. Also, (3) if the Roche model is not assumed in this analysis, then changes within the stars could cause period changes. AR Lac was the only system to exhibit a sudden period change and not be near dynamical instability.

Lsechnikov (1955) concurred with Wood's interpretation in terms of an ejection mechanism, as did Theokas (1977). Assuming that the secularly expanding subgiants are thermally unstable, Theokas utilized Martynov's (1977) proposal that macroscopic motions in the atmospheres of such stars could cause material to travel beyond the equi-potential surface, thereby escaping the system. The

decrease in angular momentum corresponding to this mass loss would produce a period change. Biermann and Lust (1960) found considerable spectroscopic evidence among many observers of very great turbulence velocities in binary components, these large velocities being indicative of prominence activity on a very large scale with the resultant ejection of material generating the measured period changes in these systems.

Following along the same lines as Wood (1950), Hall (1972) advanced the theory that changes in the orbital period of RS CVn would be explained by mass loss from the dark (spotted) hemisphere of the cool star, in much the same way that material is ejected in solar flares. Ejection of material from this dark region would occur on a continuous basis, rather than intermittently. When the dark area is on the leading edge of the star and mass is ejected primarily in the forward direction, the period of the system would be decreased. When the dark area is on the following edge of the star, the period of the system would be increased. (Hall, 1972, had originally stated that the period would be <u>increased</u> by mass ejection from the <u>leading</u> hemisphere. Arnold and Hall, 1973, corrected this to read as shown. They also changed the mass-ejecting area of the star from the fainter to the <u>brighter</u> hemisphere.) Velocities of ejection would be on the order of those of solar flares: viz., a few thousand km/sec. For an ejection velocity of 3000 km/sec, the annual mass loss required to produce the

observed period change is 10^{-6} $M_{\odot}$/yr, admittedly very large, Hall agreed. Some argument ensued, Catalano and Rodono (1974) objecting to high-velocity impulse-type mass ejection from the brighter hemisphere on the basis that it would be expected that flare-type mass ejection would originate from the darker hemisphere, where the spot activity is supposedly occurring. They also objected to the large annual mass loss required by the model. Hall (1975a) countered their first objection by stating that the mechanism for mass ejection is not known; therefore it would be presumptuous to assume that one hemisphere (either bright or dark) is a more probable site for the ejection activity. In further support he cited Vogt's (1974, 1975) observations of the flare star BY Dra, which apparently exhibits a dark region at some epochs and a bright region at others, thereby suggesting that "active regions on 'spotted stars' can be either dark or bright" (Hall, 1975a, p.223). Hall (1975a) also offered in evidence nine observed phenomena accounted for by his mass ejection process, as opposed to only four phenomena accounted for by Catalano and Rodono's (1967, 1974) tilted-ring model. Hall (1976) further countered Catalano and Rodono's arguments by offering as another possible ejection process the corotation of the ejected mass out to some Alfven radius (Oliver's suggestion to Hall: Oliver, 1983a), a mechanism which would (1) allow the observed period changes to occur with less annual mass loss because of the longer effective moment arm of this radius compared to the orbital axis of the mass-ejecting star, and (2) explain the presence of ejected

mass above the brighter hemisphere by allowing the curved path of the ejected mass to extend from the darker hemisphere to that part of the Alfven radius above the brighter hemisphere. Hall (1972) indicated that the two orientations of the dark area relative to the system when period changes occur are when the dark area faces earth, at phase 0.25 for period decreases and at phase 0.75 for period increases. Correlation of respective period decreases and increases at these two phases have also been observed in two other RS CVn stars: SS Cam (Arnold, Hall, and Montle, 1973) and AR Lac (Hall, Richardson, and Chambliss, 1976)--see Section IV. Hall (1976) stated that there would be a general tendency for periods of binary systems to decrease. Mass loss from the system would produce a net loss of angular momentum, thereby bringing on the period decrease.

Component Interaction as the Mechanism

Chambliss (1976) noted that in semi-detached or contact system period changes would be expected. AR Lac, however, is detached by a wide margin (Oliver, 1974; Chambliss, 1976), as are all RS CVn binaries (Hall, 1976). Chambliss interpreted AR Lac's substantial period changes as indicative that there is much greater interaction between its components than in "more normal" detached systems.

Other Effects as the Mechanism

While investigating the period changes in AR Lac, Hall, Richardson, and Chambliss (1976) rejected several theories previously presented by other investigators to explain the period changes:

(1) Apsidal motion was ruled out because of the similarity of the patterns of the O - C residuals for primary and secondary eclipses and because of the lack of sinusoidality of the O - C curves.

(2) Orbital motion about a third body was eliminated because of the lack of suitable periodicity of the O - C curve and because of the absence of spectroscopic evidence for a third body.

(3) Mass transfer by the Biermann-Hall mechanism (Biermann and Hall, 1973) was discounted, being inapplicable because AR Lac is not semi-detached.

(They did not offer any explanation(s) to supersede these.)

Correlations of Phenomena

Introduction

There has been much evidence gathered to indicate that several phenomena observed in both single and binary Ca II-emission stars are related.

Spectroscopic-Photometric Correlation

Kron (1950) suggested that both the Ca II emission and the flares observed in late-type dwarf emission stars originate by sunspot-like activity in the photometrically detected small brighter and fainter areas on the surfaces of these stars. Noting that in AR Lac and probably in YY Gem the intensity of the Ca II emission lines varies with orbital phase led Kron (1952) to state, "The similarity in the behavior of the emission lines with the behavior of the photometric distortions lends weight to the conclusion that

the two phenomena have a common origin" (Kron, 1952, p.315). Oliver (1971, 1974) concurred with Kron, postulating that the emission in some systems might be related to the moving photometric distortion.

Weiler's (1975, 1978) discovery that the phase of the Ca II-emission maximum coincides with the phase of the distortion-wave minimum in UX Ari, RSC Vn, and Z Her led him also to the conclusion that there exists a relationship between these spectroscopic and photometric phenomena.

Observations by Babaev (1974c,d) considered alone and also in combination with the findings of the present investigation appear to extend the distortion-wave-Ca II-emission relation to AR Lac. The interpretation of Babaev's data indicates that the observed minimum of the photometric distortion wave and the observed maximum of the Ca II emission coincide in epoch. In the present investigation the observed Ca II emission maximum coincides in epoch with the photometric distortion wave minimum predicted by Hall, Richardson, and Chambliss (1976). Also, Weiler's (1978) observation of an apparent extra-eclipse emission maximum lies on this migration curve for AR Lac as do the data points representing the observations cited above. (See Section IV.)

Further evidence of a general relationship between photometric and spectroscopic observations is provided by the non-periodic variability of the H and K emission of HD 206860, a single G0 V star, which was observed by Blanco,

Catalano, and Marilli (1978). They interpreted this behavior to indicate chromospheric activity. Intrinsic photometric variations of the star were observed to have a period consistent with what would be expected for the rotation period of a star of this spectral-luminosity type. It was therefore surmised that the photometric variations are caused by spots (active regions) associated with the observed chromospheric Ca II emission activity.

Photometric-Infrared Correlation

Discovered by Hall, Montle, and Atkins (1975), a relationship between the migrating photometric distortion wave and the infrared excess in UX Ari indicated the possibility that the same mechanism causes them both. A similar relationship might exist in AR Lac and other RS CVn systems.

Photometric-Radio Correlation

Observations by Guinan et al. (1979) of rapid migration of the distortion-wave minimum and changes in the light curve of HR 1099 (V711 Tau) evoked the suggestion that there is an association between these occurrences and the radio outbursts which were observed during the same time interval. They concluded, "Assuming that the light variations are caused by starspots on the active component, it would appear that the configuration of the spotted regions has changed significantly" (Guinan et al., 1979, p.3). Although several attempts have been made, no correlation of optical behavior (eclipses and other variations) and

radio behavior (general variability and outbursts) has been observed in AR Lac (Chambliss, 1976; Owen and Spangler, 1977). These observations were, however, by no means exhaustive; there may yet be some relationship found.

Luminosity Correlations

Gratton (1950) determined that there is a period-luminosity relationship for late-type binaries with Ca II emission. The positions plotted on an (M, log P) graph for all the systems studied fell between the limits $0.3M + \log P = 1.0$ and $0.3M + \log P = 2.5$. Wilson and Bappu (1957) discovered a relationship between the logarithm of the H and K emission-line widths and the absolute magnitude of stars with Ca II emission: the line width varies as the one-sixth power of the luminosity.

Conclusion

Based upon the results obtained in these observing programs it seems evident that relationships between the Ca II emission and the photometric distortion wave and between the distortion wave and infrared and radio emission exist in many of the RS CVn systems and perhaps will be discovered in all of them. The two luminosity relations have been verified for a wide range of system magnitudes.

Evolution of Stars with Ca II Emission

Introduction

There are many arguments which have been posed regarding the age and evolutional stage of stars with Ca II emission. In particular, much controversy has arisen

regarding the age and stage of the RS CVn stars. Attempts have been made to find relationships between the ages of these systems and their various physical, photometric, and spectroscopic parameters.

Stage of Evolution

Pre-main sequence

The evolutionary status of binary systems with undersize (not filling their Roche lobes) subgiant secondaries was investigated by Roxburgh (1966), who advanced the hypothesis that such systems are in a pre-main sequence stage and that their present binary state has resulted from the fission of a rapidly rotating single star. Following up on Roxburgh's study, Field (1969) considered eighteen such systems, AR Lac included. For the primaries of all the systems, good agreement was obtained between ages calculated from the radius and from the effective temperature. This result indicated that the pre-main sequence tracks chosen for the primaries were "adequately" represented by his derived equation relating mass, radius, and effective temperature of the primary as a function of time. For the AR Lac secondary and for the majority of secondaries considered, however, the radii calculated from the primaries' ages differed considerably from the observed radii of the secondaries, thereby indicating that the hypothesis of a pre-main sequence stage is in error. As a result of the fact that the pre-main-sequence-contraction hypothesis was not

self-consistent for all the systems studied, he proposed that "Kopal's [1958] 'systems with undersize subgiant secondaries' form an observational rather than an evolutional class of objects" (Field, 1969, p. 419). Based in part upon the extreme strength of the H and K emission in the RS CVn systems, Hall (1972; 1974; 1975a,c), too, made the suggestion that they are in a stage of pre-main sequence evolution, thereby placing them at a phase between the T Tauri stars and the late-type dwarf emission stars.

Post-main sequence

To the contrary, Oliver (1974) favored the view that the systems in the RS CVn classification are in a long-lived, somewhat evolved stage, this conclusion being based on the observed characteristics of the components and on the large number of systems in this group.

Biermann and Hall (1976) argued that the most probable stage of evolution for the RS CVn systems is that they are in a post-main sequence thermal phase following fission of a rapidly rotating single main-sequence star. In particular, Hall (1975b) concluded that WW Dra could not be in a pre-main sequence stage because both components of the system are more massive than their F8 V visual companion, ADS 10152 B. Given the usual premise that stars in a system are formed coevally, the more massive stars would have evolved to a more advanced evolutional stage than the less massive one in the same length of time. The facts that (1) the RS CVn systems occupy the Hertzsprung gap, (2) they are

not associated with regions known to be presently engaged in star formation, (3) the post-main sequence lifetimes are 100 times as long as the pre-main sequence lifetimes of stars of the same mass and size, (4) the more massive star in a system usually has the larger radius, and (5) two systems have low-luminosity main-sequence visual companions which could not have evolved to the main sequence ahead of the higher-mass, higher-luminosity components of the spectroscopic binaries constitute five pieces of "circumstantial evidence" (Popper and Ulrich, 1977, p.L131) from which Popper and Ulrich also inferred that these stars are in a post-main sequence evolutional stage. They suggested that these systems have evolved through the main sequence by the normal processes of single-star evolution. In the post-main sequence phase the RS CVn instabilities would become manifest when the stars have exhausted their core hydrogen and have developed convective envelopes. At this stage normal single-star evolution would be accelerated by mass exchange or loss through a mild stellar wind from the larger component as the stars expand toward the giant stage (Popper and Ulrich, 1977). Oliver (1974) proposed a model with slow mass transfer (much like the solar wind) "leaking" mass through the inner Lagrangian point. In support of this picture Popper and Ulrich offered the fact that mass flow is evidenced by the observed period changes in these systems; and active surfaces and extra-stellar mass are revealed by the observed strong Ca II emission, the

variable H-alpha emission, the infrared excess, and the variable radio emission. From Popper and Ulrich's (1977) theory, Naftilan and Drake (1977) inferred that AR Lac is in a thick-shell-burning phase of evolution.

Further evidence of a post-main sequence stage for Ca II emission systems was provided by Young and Koniges (1977). The observations that longer-period systems without Ca II emission are less evolved and have larger orbital eccentricities versus the "strong tendency" (Young and Koniges, 1977, p. 841) for systems of similarly long period and with H and K emission to be evolved and to have zero eccentricity led Young and Koniges to propose that the time scale for circularization of orbits is long on the stellar evolution time scale. For stars from $1\text{-}3M_{\odot}$ in longer-period systems (15^{d}-30^{d}) circularization would take place during the post-main sequence phase when tidal coupling would be stronger because of the increased radii of the stars. For the shorter period systems, however, circularization would be completed during the main-sequence stage. Following this line of reasoning, the fact that AR Lac is a short-period binary ($1^{d}983$: Rugemer, 1931) with an orbit of zero eccentricity (Sanford, 1951; Chambliss, 1976) therefore indicates that it has completed its main-sequence stage.

Circumstellar matter, component masses, and population count. Additional evidence of evolutionary stage is provided by the presence or absence of circumstellar matter, measurements of the masses of the stellar components in

binaries, and the population count of the systems in existence.

The observations in the present investigation and in other investigations (Kron, 1947; Sanford, 1951; Catalano, 1973; Hall, 1976, Rhombs and Fix, 1977; Naftilan and Drake, 1977; Owen and Spangler, 1977) of pre- and post-primary eclipse depressions in the Ca II emission and in the light curve of AR Lac indicate the presence of a circum-secondary cloud of material. Further, Rhombs and Fix (1977), indicated that the most likely source of the apparent metal deficiency in the AR Lac secondary (Miner, 1966; Naftilan and Drake, 1977) is free-free emission from circumstellar high-temperature gas flowing outward from the cool component. The emission from this circumstellar material would fill in absorption lines and diminish the equivalent widths of weak metal lines. Miner's (1966) line of reasoning, however, had produced a contradicting result. He deemed it improbable that the metal deficiency which is found in every eclipsing binary would stem from their <u>all</u> having been formed in metal-poor regions. He contended that there must be some mechanism in these systems which is responsible for depleting metal content or masking absorption by metals. Mass ejection would not fulfill the necessary requirements because it would be more likely to deplete the hydrogen-rich outer layers, thereby producing just the opposite of the desired effect. Further evidence, however--see below--overruled Miner.

Measurements of the infrared excess of AR Lac led Atkins and Hall (1972) to the conclusion that it seems to be an intrinsic property of the star rather than being an extrinsic characteristic arising from a source such as a circumstellar dust cloud. Countering this view, Rhombs and Fix's (1977) observations of AR Lac indicated that free-free emission from high-temperature circumstellar material flowing outward from the secondary would account for the observed infrared excess. In addition, they stated that this emission from this material would be the most probable source of AR Lac's ultraviolet excess, which increases below 4600A as wavelength decreases.

Observations of the hydrogen spectrum of AR Lac prompted Naftilan and Drake (1977) to propose that a circum-secondary envelope exists in the AR Lac system, thereby also challenging previous statements to the contrary. They determined that the symmetry of displacement of emission cores from the centers of the Balmer lines of the secondary of AR Lac indicates the presence of a circum-secondary non-equilibrium corotating envelope or disc which would intermittently lose mass to the primary.

The existence of this circumstellar material in the AR Lac system indicates that some mass exchange has occurred (and is perhaps still occurring, because the cloud may be unstable). Mass exchange is an additional characteristic of a post-main sequence phase. Oliver (1974) and Popper and Ulrich (1977) each proposed for the RS CVn systems a model

which involved a solar-wind-like slow mass transfer. This mass flow is revealed in the RS CVn stars by their enhanced chromospheric activity (Morgan and Eggleton, 1979) and by their period changes (Popper and Ulrich, 1977.).

In all early investigations the larger of the two components of AR Lac was measured to be the slightly more massive one, so that evolution of the larger, more massive star was advancing slightly faster than that of the smaller, less massive one, in the traditional sense. In his mass measurements of improved precision, however, Popper (1967) determined that the masses of the two stars are reversed. The RMS errors overlap though, thereby indicating that the stars are of essentially equal masses. The components therefore sit on the fence with regard to evolutional analysis on the basis of mass. Perhaps the mass exchange is such that the two stars see-saw back and forth evolutionally: as one's mass increases and the other's decreases, one surges ahead for a short period; then the other accumulates enough of the former's cast-off mass to tip the scales in its favor, and it surges ahead. This type of activity would take an extended period of time, thereby causing the RS CVn stage in the lives of the system components to be an enduring one rather than an ephemeral pre-main sequence one.

This picture would confirm Oliver's (1974) assertion that the RS CVn stage is a long-lived (post-main sequence) one in view of the large number of these systems in

existence. To lend additional support to a high population, Hall (1976) calculated the space density of the RS CVn systems to be very large. Further, new RS CVn systems are continually being discovered.

Popper and Ulrich (1977) contended that the RS CVn characteristics arise when the core hydrogen is exhausted and convective envelopes have developed. Morgan and Eggleton (1979) concurred, asserting that the RS CVn characteristics would be most probable in systems in which the more massive component has evolved to the base of the giant branch, but has not exceeded its Roche lobe, and the less massive component has evolved to a point just before or just after core hydrogen exhaustion. Further, mass loss by a stellar wind from the more evolved component could be consistent with the enhanced chromospheric activity observed in these stars.

Additional evidence of the evolutional stage of the AR Lac components, presented by Lacy (1979), is somewhat contradictory. It appears definite that neither component is on the ZAMS, but other data place the stars in mildly questionable states. According to Lacy's (1979) data, the low luminosity of the AR Lac primary places it below the ZAMS, a characteristic which Lacy associates with primaries of systems which have undergone mass exchange. The large radius of the primary, however, places it above the ZAMS. The low luminosity and the radius of the primary further indicate that the star has not yet reached the point of

core-hydrogen exhaustion. The results for the secondary are slightly less ambiguous. Its radius and luminosity establish its position above the ZAMS. Its large radius indicates that it has reached the stage of core-hydrogen exhaustion, but its low luminosity points toward an earlier stage.

Based on the facts that mass exchange has occurred, that the radii of both stars place them above the ZAMS, and that both stars are close to, if not at, the point of core-hydrogen exhaustion, it can probably be concluded from the data of Morgan and Eggleton and Lacy that both stars are in stages following rather than preceding the main sequence.

Ca II Emission and Li Absorption. The strengths of both Ca II emission and Li absorption have been found to be indicators of aging and evolutional stage.

An inverse correlation between the chromospheric activity and age in main-sequence stars was discovered by Wilson (1963). He suggested that the chromospheric activity would be a function of the average magnetic field strength and indicated by the strength of the Ca II emission. He pictured all main-sequence stars of the same spectral type being born with approximately the same average magnetic field strength, which could not be maintained due to insufficient dynamo action. The average magnetic field strength would therefore diminish with age. The diminution of the field strength would be attributable to the transformation of the magnetic energy into other forms which

could be radiated away by the star. Further evidence (Wilson and Skumanich, 1964) indicated that H and K emission intensity in main-sequence stars is an indicator of age alone and is independent of the circumstances of birth. Blanco et al. (1974) confirmed that the K-line emission flux and the surface magnetic field for main-sequence stars decrease with increasing stellar age. They determined further that for stars of the same age the K-line emission flux is a function of spectral type, exhibiting a maximum at K0.

Inducing a line of reasoning parallel to those of Wilson and Blanco et al., the extreme strength of the Ca II emission in the RS CVn systems was partially responsible for Hall's (1972) placement of the stages of these systems in an intermediate position between those of the T Tauri stars and the late-type dwarf emission stars.

Contradicting the foregoing results, Wilson's (1976) comparison of a group of single stars having strong Ca II emission to a group with weak Ca II emission demonstrated that the space velocities of both groups extend over similar ranges. From this evidence Wilson concluded that the degree of chromospheric activity is not a function of age, but is instead determined by some intrinsic property of the star.

Opposing Wilson's (1976) view, Young and Koniges (1977) arrived at the conclusion that strong chromospheric activity, indicated by strong Ca II emission, is not exclusively attributable to youth. They indicated that

there is a growing consensus that in binaries with Ca II emission the situation is, in fact, quite the contrary: chromospheric activity, as indicated by the Ca II emission strength, intensifies as the components evolve. They confirmed this conclusion by their own spectra of late-type binaries with strong Ca II emission, which showed no Li I 6708 absorption line. (Young and Koniges stated that Li is thought to be present only in very young stars--see Li, below.) Coupling this spectroscopic evidence with Popper's (1977) evidence that Ca II emission in binaries is strongest when one of the components is evolved completed the link between strength of emission and aging. Based on this relation, the AR Lac system's strong Ca II emission observed in this investigation therefore also places AR Lac in a classification of evolved stars as determined by Popper's (1977) evidence that Ca II emission in late-type binaries is the signature of evolved systems rather than of unevolved ones.

The relationship between the Li 6708 absorption lines and evolutional stage was discovered as the result of the efforts of several observers. Conti (1970) stated that every young star he had observed exhibits considerable amounts of Li, a characteristic he considered to indicate for "certain that that star was not evolved" (Conti, 1970, p. 100). Although it is observed that "some old stars exist with appreciable amounts of Li (Conti, 1964; Wallerstein, 1966; Feast, 1966)" (Wallerstein and Conti, 1969, p. 109),

the absence of the Li feature would allow one to be "reasonably sure that the star was not a contracting case" (Conti, 1970, p.100). No Li 6708 has been observed in AR Lac (Naftilan and Drake, 1977; Young and Koniges, 1977), thereby almost certainly assuring its position in a non-pre-main sequence stage.

The general conclusion regarding Ca II emission and aging is that the overwhelming evidence points toward the emission intensity's being a direct function of age and not an intrinsic property of the individual star as Wilson (1976) suggested.

Overall, the observations regarding evolution strongly favor a post-main sequence stage for the RS CVn systems.

Ages of the RS CVn Systems

Read from Field's (1969) graph, the age for the AR Lac primary is 1.125×10^7 years. The age for the AR Lac secondary is not in accord, however, thereby rendering this age calculation invalid for the AR Lac system.

Hall (1972) gave no numerical value(s) for the age(s) of the RS CVn systems; he merely indicated that their ages are between those of the T Tauri stars and the late-type dwarf emission stars.

Montle (1973) computed the age range for the RS CVn stars to be from $1-4 \times 10^8$ years (average age 2×10^8 years) on the basis of their average distance from the plane of the galaxy and their average velocity perpendicular to the galactic plane, quantities which he calculated from their

distances, galactic latitudes and longitudes, systemic radial velocities, and proper motions.

Using Wielen's (1974) calibration of velocity-dispersion-versus-age with Montle's (1973) value of 10 km/sec for the velocity dispersion of the RS CVn stars, Hall (1976) determined their ages to be about 2×10^9 yr.

The result of Morgan and Eggleton's (1979) calculation concurred with Hall's (1976), but was arrived at by a different method. The probability of occurrence of eclipses of depth about 0.8 mag or deeper in binaries which have circular orbits and have not evolved to the point of mass transfer is maximized for an age of 2×10^9 yr at the averaged RS CVn characteristics: fairly low masses (primary mass $1\text{-}2M_\odot$), mass ratio close to unity, hotter star of spectral type later than about F0, cooler larger star of spectral type about K0 IV, and period $2\text{-}10^d$.

Popper and Ulrich (1977) determined the age of the RS CVn group to be 3×10^9 years by analysis of the velocity dispersion relative to the local galactic standard of rest.

The measurements made in the present investigation do not provide evidence which can be used to establish the age of AR Lac. The valid results cited above, however, indicate that the ages of the systems in the RS CVn group lie between 1×10^8 and 3×10^9 years.

Other Evolutional Effects

Naftilan and Drake (1977) found the macroturbulence velocity for the AR Lac secondary to be anomalously high for

a subgiant, a characteristic which they suggested could be related to the formation of the chromosphere.

Summary

Although the observations of the present investigation cannot alone establish precisely the site of or the mechanism for the Ca II emission in AR Lac or the age or the evolutional stage of AR Lac, they do allow the system to be assigned to a general evolutional category by supporting the observations of others.

The layer of AR Lac (and the other RS CVn stars) in which the Ca II emission arises is undoubtedly the lower chromosphere, as evidenced by solar analogy and by measurements of (1) the radial velocity of the emission and (2) the thickness of the emitting layer in AR Lac. Radial velocity measurements favor an emitting layer attached to the star(s) rather than some external emission site such as a gas stream.

The behavior of the Ca II emission reveals that it is not restricted to only one surface position on the stellar components. Measurements of the changes in Ca II emission with phase indicate that within that emitting layer some, though not all, of the emission from AR Lac arises at the tips of the tidal bulges. The entire stellar surface is responsible for a distributed background of Ca II emission. Sudden, non-periodic changes in emission are produced either by (1) flares or prominences or by (2) eclipse and rotation around the limb of isolated large emission regions.

The underlying emission agent is apparently a temperature increase, which probably results from the collision of opposing streams of material within the star. Normal collision already present in a star may be enhanced by currents, streams, or whirlpools (vortices) of material within the stars being induced by (1) the close binary association of the stars, (2) differences in gravitational acceleration over the stellar surfaces, and (3) sunspot-like activity, flaring, or prominences. Alternatively, this collisional chromospheric heating might perhaps be effected by acoustic energy transport as a result of enhanced tidal coupling as the RS CVn stars expand toward the giant stage.

On an atomic level, the question of whether the mechanism of Ca II emission in AR Lac is ordinary excitation or is the final step in a fluorescence cascade has apparently not been discussed since the late 1940's and is perhaps still uncertain. The Ca II emission might also possibly result from a selective excitation by emission from atoms of another element with a strong emission line coincident in energy with the H and K lines.

The formation of and changes in other spectral lines (H emission, Fe, and Ce) in AR Lac can apparently be explained by gas streams, bombardment by extra-component particles, or a turbulent vortex.

Radio emission is probably not produced by thermal bremsstrahlung from circumstellar material, a more likely source being magnetobremsstrahlung from relativistic

electrons. The radio source is much larger than the system stars themselves.

By inference based on the association of solar magnetic fields with sunspots and with strong Ca II emission, there are possibly magnetic fields associated with the starspots in AR Lac. No measurements of the Zeeman effect have been attempted, however.

Irregular light-curve variations indicate that the surface luminance of the AR Lac primary is less uniform than that of the primary. The intrinsic variability of the primary is not caused by pulsation, but may be generated by starspots, flares, or prominence activity.

(1) Pre- and post-primary-eclipse Ca II-emission depressions and light-curve depressions and (2) metal deficiencies are attributed to enhanced absorption by a circum-secondary envelope of material resulting from mass ejection from the secondary. Infrared and ultraviolet excesses and symmetry of the Balmer emission also result from the presence of this circumstellar envelope.

Pulsation, a tilted ring of circum-secondary material, gas streams, tidal effects, and the reflection effect have all been ruled out as mechanisms for the photometric distortion wave in RS CVn stars. The photometric distortion wave and its changes in rate of motion and in amplitude are best explained by the presence of a group of large starspots which migrate in longitude, drift in latitude, and change with latitude in size, number, migration rate, and drift

rate on a differentially rotating star, much as sunspots do. It is assumed that the starspot drift is driven by a pole-equator temperature differential (poles hotter). The spots are apparently convection cells extending throughout the convection zone, the depth of which governs their size: the deeper the zone, the larger the spots. Because the RS CVn stars have deep convective shells, but are not completely convective, the spots would be moderately large, be restricted to latitudes away from the polar regions, and would produce large-amplitude periodic brightness changes as the spots rotate around the limb and are eclipsed. RS CVn stars might evolve through three spot-migration and spot-position categories, each rooted in the depth of the convective zone. Fast differential rotation and tidal effects due to the presence of the companion star might enhance the magnetic field-line breakthrough effect, generating more and larger spots than on the sun.

Photometric and spectroscopic evidence exists demonstrating the observability not only of large groups of starspots but also of large individual spots on the AR Lac components. When the spot groups face earthward, the photometric distortion wave minimum and the Ca II emission maximum are observed. Although one theoretical model contends that individual spots would not produce a sufficient variation in magnitude to be observable, the differential magnitudes in the observations indicating individual spots exceeded the minimum theoretical detectable

differential magnitude by at least a factor of 100. It is concluded, then, that large individual spots were observed.

Abrupt period changes undergone by AR Lac cannot be explained by intrastellar instabilities, faster-than-synchronous rotation of the fainter component, apsidal motion, orbital motion about a third body, or mass transfer by the Biermann-Hall mechanism. Some type of mass ejection, by (1) eruptive prominences or (2) more-or-less-continuous ejection of material (like the solar wind), both associated with a migrating spotted region (either bright or dark--the question remains), correlates well with the observation of period increases and decreases when the spotted region is on the following and leading hemisphere of the star, respectively. The mass loss is apparently enhanced by component interaction in AR Lac.

The epoch of the (1) Ca II emission maximum, (2) the photometric distortion wave minimum, and (3) period changes are unquestionably correlated in RS CVn, UX Ari, and Z Her. Apparently the tri-fold relationship obtains in AR Lac also, the relationship between the latter two quantities having been almost definitely established and the relationship between the former two quantities having been tentatively established for AR Lac.

Correlations of photometric behavior with infrared and radio behavior in UX Ari and V711 Tau, respectively, offer some basis for the supposition that such relationships may exist in other RS CVn stars. The possibility of an infrared

correlation has not been investigated for AR Lac, and results of attempts at radio correlation have so far been null.

AR Lac obeys the Wilson-Bappu relation and Gratton's period-luminosity relationship for late-type binaries with Ca II emission.

The evolutionary status of AR Lac is decidedly not pre-main sequence. The overwhelming majority of the evidence places the RS CVn stars in a post-main sequence stage, the more massive component having evolved to the base of the giant branch and the less massive component having evolved to a point just before or just after core-hydrogen exhaustion. Slow, not rapid, mass exchange (by a stellar wind) has been, and possibly still is, occurring, perhaps generating a situation (in AR Lac, at least) in which the components see-saw back and forth evolutionally. Evidence for such a stellar wind in RS CVn stars is their enhanced chromospheric activity and their period changes. Based on the extreme strength of their Ca II emission, their lack of Li absorption, their galactic positions and velocities, their orbital characteristics, their physical characteristics, and their population count, the RS CVn stars can almost certainly be fixed firmly in a long-lived post-main sequence stage of evolution, at an age somewhere between 1×10^8 and 3×10^9 years.

SECTION VI
FUTURE INVESTIGATIONS

Introduction

There are several valuable spectrogram analyses, necessary equipment modifications, and desirable observations which suggested themselves during this investigation.

Spectral Analysis

Series of spectra of three RS CVn systems other than AR Lac (UX Ari, Z Her, V711 Tau) were obtained as a part of this investigation. UX Ari and Z Her are eclipsing members of this group; V711 Tau is a non-eclipsing member. A complete analysis of these spectrograms would supplement the analysis already performed herein for AR Lac. Results of such an analysis would allow a comparison (though incomplete due to the lack of data) of the behavior of the Ca II emission in eclipsing members of the group to that of a non-eclipsing member.

A series of high time-resolution and high grating-resolution spectra of RS CVn were obtained in 1974 by Oliver at KPNO. Preliminary scanning microdensitometer tracings of these spectrograms revealed that the H and K emission of this system exhibits short-term changes. Such variations are indicative of a high level of chromospheric activity (such as turbulence) or of occultation of a

localized emission area (Weiler, 1967; Naftilan and Drake, 1977; Struve, 1952; Weiler, 1978). Construction of line profiles and complete measurement of these profiles would contribute to the understanding of the structure of the stars in this system and similar systems.

Analyses of the data for these four systems were not included as a part of this dissertation for two reasons:

(1) The coverage of the phase cycles was so incomplete that no valid conclusions could be drawn regarding the behavior of the Ca II emission either during eclipse phases or during other parts of the cycles. (The primary culprit which prevented observations was the weather.) Many additional data in combination with those already obtained are necessary to make a significant contribution to the body of knowledge of these systems.

(2) Failure of part of the electronics of the scanning microdensitometer forced the postponement of further data reduction until substantial equipment modifications could be completed.

Equipment

Several deficiencies in the available equipment rendered the procedure for obtaining the data and performing its subsequent analysis cumbersome to say the least. The observation-and-data-reduction system is at present most severely limited by its data-analysis capabilities.

Exposure times for the spectrograph were as much as a factor of 10 times longer than those for similar spectrographic systems at other observatories (Oliver, 1976a). A factor of approximately 4 can be accounted for by the degraded reflectivity of the 76-cm primary just prior to its scheduled time for resurfacing. The remaining factor of about 2.5 can presumably be attributed to low grating efficiency, because this is the only unknown in the entire telescope-spectrograph system. Boller and Chivens offered no specifications for the grating efficiency (Oliver, 1976). Ray tracings revealed no deficiencies in the apertures or the optical design of the system, and calculations of light losses at the collimator and within the spectrograph camera could not account for this large a factor.

Another effect on the exposure time (which was accounted for) was the order of the blaze of the grating. Because the gratings in the present spectrographic system are blazed in the third-order blue, the dispersion is increased by a factor of approximately 3 over that of a first-order blaze (a desirable effect); but the exposure time is also increased by a factor of 3 (an undesirable effect) because the light intensity decreases as order increases.

In order to remedy both problems (inefficiency and low light intensity) simultaneously, the present gratings should be replaced by a high-efficiency grating blazed in the first-order blue. As a suggested replacement, a grating

(available from Boller and Chivens: Wheeler, 1973) ruled at 1200 lines/mm, blazed at 4000 A in the first-order blue (very near the K line, 3934 A), with a blaze angle of 14°, would provide nearly 2.5 times the dispersion and resolving power as the present grating, yet allow about 7 times as much energy to be incident on the plate at that wavelength. In order to achieve the same plate density, the exposure time would therefore be reduced by a factor of about 7.

In order to attain a more accurate assessment of the correct plate exposure (which is determined by the intensity of light received and the length of time of the exposure), the exposure meter could be reassembled using a more sensitive photomultiplier tube, thereby allowing discrimination between a bright sky and a faint star. The resulting elimination of "guestimation" of exposure times would in turn eliminate plates too thin to show emission reversals and plates too overexposed to be measurable.

The imprecise sensitometry procedure could also be greatly improved. At present the stellar spectra are obtained and developed under one set of conditions, whereas the sensitometry plates are a different set of plates exposed and developed under a different set of conditions. Such a situation is not conducive to the production of sensitometry plates which are to be used as standards for absolute spectral plate emulsion density comparisons of the highest precision. This imprecision could be eliminated by

(1) modification of the spectrograph camera system so that the sensitometry spots are applied directly to the stellar plate simultaneously while the spectrum is being obtained, or

(2) construction of an auxiliary sensitometry box in which the stellar plate would receive the same exposure time in the same wavelength region immediately after the spectrum is obtained. (Plans for construction of such a box were being drawn up by Fitzgibbons, 1980.)

The tedious and time-consuming procedure of plate analysis could be greatly improved by extreme modification of the equipment used in the intermediate steps of digitization of the spectral data. At present it is a multistep process involving the scanning microdensitometer, the transmission densitometer, and much manual work constructing characteristic curves and converting deflections into emulsion densities, which are in turn converted into intensities, which are finally numerically integrated over the line profile to produce an equivalent width. This lengthy process could be eliminated by modifying the scanning microdensitometer to digitally record density and/or deflection data directly from the spectrum and from the accompanying sensitometry spots. A computer program could be designed to perform the analysis of the digitized data. Oliver (1980) planned and has completed (1982) such a modification, which would employ the PET computer directly linked to the scanning microdensitometer.

Other necessary additions to the microdensitometer are wavelength markers which are recorded during tracing (or noted during digitization) and/or a means of tracing (or recording digitally) the comparison spectrum simultaneously with the stellar spectrum.

Radical modification of the photometric sensitivity of the microdensitometer is also necessary. Under naked-eye or microscopic examination many under- or overexposed spectra exhibit emission reversals. The range of densities over which the instrument can operate, however, is so limited that only plates which are like the baby bear's porridge (juuust right) can be traced. (This investigator has long suffered the frustration of the "Goldilocks Syndrome.") A system which is not even as sensitive a discriminator as the human eye is somewhat less than adequate for probing the secrets of the universe. In order to remedy this situation, the electronics of the densitometer could be altered to allow it to measure low total and differential light levels. This modification would increase the capability of the system in two ways:

(1) Spectra which are widened only one-third to one-half of the minimum the present system can accommodate (because of the low level of light transmitted) could be measured, therefore allowing (a) the analysis of spectra of this description which have already been obtained and (b) the future reduction of exposure times by a factor of 2 or 3. This enhancement of time resolution would be of great

value in the observation of short-lived phenomena such as partial phases of eclipses of binary stars, flares, and formation and dissolution of starspots.

(2) Spectra with high fog levels or spectra which are very thin could be measured. (Both are cases which result in very small differences between spectrum density and fog density.) This augmented capability not only would allow the use of many previously obtained plates which cannot be analyzed with the present system but also would relieve the present restriction on the allowable range of measurable densities.

The foregoing modifications of the spectrographic and data analysis systems will produce data of higher precision and allow almost on-the-spot data reduction (rather than forcing years of waiting for results).

The problems of emulsions and the microdensitometer will be circumvented completely by the completion of the spectrum scanner with its direct video display and disc storage system (Oliver, 1983b).

Observations

In the present investigation a number of spectra were obtained of the non-eclipsing RS CVn binary V711 Tau. This system has an eighth-magnitude visual companion which shares the same right ascension; consequently the alignment of the visual system is along the spectrograph slit, and the visual companion is included in the exposure. Although the contribution of this companion is faint, it does render the

resulting spectrum a composite, which would be extremely difficult to separate into the components contributed by each part of the visual system. It is mechanically possible, however, to rotate the slit of the spectrograph 90° to eliminate the light from the visual companion. V711 Tau could then be trailed along the slit in declination rather than in right ascension, thereby obtaining a spectrum of the RS CVn system alone.

Emission in the sodium D lines (5890A and 5896A, produced by neutral sodium) has been searched for in some stars (Young and Koniges, 1977). Obtaining a series of spectra at these wavelengths would allow the construction of a light curve at the D lines similar to the one constructed at the K line in the present investigation. If the image tube (see Section II) which was used in an attempt to obtain spectra of the D lines can be redesigned to function under ambient conditions, such spectra can be obtained.

The Li I 6708 line has been sought, but not observed, in AR Lac (Naftilan and Drake, 1977; Young and Koniges, 1977). Measurements of the strength of this line in AR Lac might yield some supplementary data which would establish even more definitely the age and the evolutional stage of the system. A strong Li I 6708 line is the mark of a very young system (Wallerstein and Conti, 1969). All young stars observed by Conti (1970) had considerable amounts of Li, a characteristic which he considered to be an almost certain indicator that the stars are not evolved. The presence of

Li does not, however, provide incontrovertible evidence of youth or of an unevolved stage, because there are some old stars which exhibit this line (Wallerstein and Conti, 1969). On the other hand, the absence of the line does automatically indicate with reasonable certainty that the system is old or evolved (Conti, 1970). The presence of a strong Li line in AR Lac would indicate that it might be a youthful system, and the absence of the Li line would lend further credence to the precept that AR Lac is evolved.

Many investigators have repeated Gratton's (1950) assertion that the Ca II emission in binary stars is much stronger than that in normal single stars; however no conclusive evidence to support this statement has ever been presented. (Perhaps Gratton misread or misunderstood Struve's (1945) statement that the number of Ca II-emitting binaries, not the strength of their emission, is greater than that of single stars.) Very crude comparisons (as stated by the observers involved) have been made of Ca II emission strength in hundreds of stars and systems (Adams and Joy, 1931; Joy and Wilson, 1949; Wilson and Bappu, 1957; Young and Koniges, 1977); however, no one has performed a study specifically for the purpose of establishing whether a disparity in emission strength exists between single stars and binaries. Also, of a total of 734 stars observed in these investigations there were only 54 binary systems (explicitly listed as such) represented. Further, the authors used various relative criteria to judge the emission

strengths; as a result the spectra were not all measured to the same standard. Because of the paucity of data based on the same standard of comparison, a program of great interest would be a precision survey of large numbers of single and binary stars which exhibit Ca II emission. The single stars should be observed during an entire rotation so that any variability in their emission due to rotation can be observed. The binary stars should be observed at all phases and for several epochs in order to take into account any variability in their emission due to eclipses and/or migration and rotation of emission regions. The absolute intensities of the Ca II emission of all spectral and luminosity classes of Ca II-emitting stars should be compared to determine what relationship exists among all of these factors (duplicity, surface temperature, absolute magnitude). Determinations of distributions and sizes of the emitting areas could be made in some single and binary stars, and a study of the rotation of single stars could be made using the emission variations as a rotation indicator. The data from these observations would also contribute to the determination of the position (in latitude) of the emission regions, the spot-position categories, the migration categories, the resultant (possibly) evolution-based categories, and the lengths of starspot cycles. For the RS CVn stars in particular the ratio of the emission of each component in a system relative to the continuum of the cooler component could be compared to that for single

subgiant K0 field stars. Because the RS CVn systems are detached, it would be expected that these ratios would be nearly equal, indicating that rapid mass transfer has not taken place (Oliver, 1976b). The period variations in these stars, however, imply that some mass transfer, though slight, must have occurred; consequently an observation program of this type would yield further information on the evolutional stage of the RS CVn systems. Long- and short-term variations in the emission of the RS CVn systems indicate a dynamic chromosphere (Weiler, 1967; Naftilan and Drake, 1977; Weiler, 1978). This observational program would therefore also obtain information on the structure of these stars.

The aforementioned series of observations of the RS CVn systems (which would include the bright newly discovered systems HR 5110 and HD 224085--see Table 2) will allow the behavior of the Ca II emission of the eclipsing members of the group to be compared to that of the non-eclipsing members. Unhampered by intervening eclipses, observations of the non-eclipsing stars at all phases would indicate whether the emission is localized, because emission would disappear at phases when the emitting hemisphere is anti-earthward. The non-eclipsing systems might also shed further light on the mechanism of the emission. In RS CVn eclipsing systems which exhibit emission in only one component, good time-resolution spectrograms taken during the partial phases of the eclipse of the emitting component

would allow examination of the brightness distribution of the emitting region in as much detail as is possible.

For reduction of the data, simultaneous U-photometric observations would be necessary in order to establish the absolute intensity of the U continuum of the stars at the times of the spectrographic observations.

All of the suggested observations necessitate time resolution of 20^m or better, a requirement which should be easily achievable with the modified equipment.

Epilogue

A span of eighty years of observation has yielded a profound lack of satisfactorily corroborative results among observers of AR Lac. This circumstance demands the establishment of a regular coordinated program of further extensive simultaneous observations in all regions of the spectrum.

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BIOGRAPHICAL SKETCH

Sara Witherow Hoffman was born in the South and has spent most of her life in the South, having lived in Memphis since she was a child. She began her career in astronomy early, collecting astronomical information on planets and stars from about age four.

After graduating from high school as a Merit Scholarship Finalist, she received her undergraduate education from Southwestern At Memphis, where she was awarded two National Science Foundation grants for research in physics and an assistantship to teach the introductory physics laboratory for physics majors. She also received the French Government Book Award for the most outstanding scholastic achievement in French I. She was elected to membership in Sigma Pi Sigma Physics Honor Society and Chi Beta Phi Honorary Science Fraternity. She was also a reporter for the college newspaper, The Sou'wester, and a member of the Southwestern Singers. She earned enough hours for majors in both physics and mathematics, and elected to receive her degree in physics. She was graduated from Southwestern as the first girl to receive the degree of Bachelor of Science with Honors in Physics. The degree "with Honors" is not equivalent to the usual cum laude (with honors) designation, at the low end of the hierarchy of

honor degrees granted by most institutions. To the contrary, the degree "with Honors" was, at the time of the author's graduation, the highest honor which Southwestern conferred on its graduating students. To be awarded this honor degree required not only a high grade-point average and exceptionally high scores on the four comprehensive examinations required for graduation but also a year of enrollment in Honors Research, culminating with a thesis. Her Honors Thesis was entitled "The Infrared Spectral Reflectivities of Ice, Snow, and Solid Carbon Dioxide."

Her acceptance into the doctoral program in physics at the University of Tennessee at Knoxville was accompanied by the award of a graduate assistantship by the Department of Physics. An interest in teaching coupled with the lucrative offer of a (tax-free!) two-year Ford Foundation grant enticed her to become a participant in the non-terminal Master of Arts in College Teaching in Physics program, which is an enriched Master of Science degree program requiring sixty hours of coursework in graduate physics, graduate mathematics, and teaching seminar (rather than the usual forty five hours in physics alone for an M.S.), plus two years of practical teaching experience being an instructor of the three-quarter sequence of five-credit-hour college-level physics lecture and laboratory courses. During her sojourn at UT, she was active in organizing the Knoxville Astronomy Club. She was graduated with a non-thesis MACT in Physics with a minor in mathematics.

While at the University of Florida pursuing her Ph.D. in astronomy with a minor in physics, she held a graduate assistantship in the Department of Physics and Astronomy, was an instructor in the undergraduate astronomy laboratory program, served for two years as the Coordinator of that program, contributed much of the material for the astronomy laboratory manual (which was later published), and was the designated substitute for professors in the introductory astronomy lecture sections. The research presented in her dissertation constitutes the first UF dissertation in the field of stellar spectroscopy. Further, her record-breaking longevity as a graduate student in astronomy at UF qualifies her as the most nearly tenured graduate student in the department. . . Her extracurricular activities included being instrumental in the founding of the RHO Sunshine Club and the Florida Astronomical Society, having held office as secretary, vice-president for publicity, and president in the latter organization. In addition to those posts, she has been the editor-in-chief and the principal journalist for the FAS publication, the ASTROLOG, and has been interviewed on numerous local radio and television programs for the purpose of promoting astronomy to the general public.

Currently a tenured academic faculty member in the Natural Sciences Area at Santa Fe Community College, she instituted the present SFCC astronomy program, which includes courses that have become extremely popular, but at

the same time have been maintained at a rigorously demanding college level of difficulty (ask her former students!). She has also contributed considerably to the construction of new courses in physical sciences and the restructuring of other courses in physics and physical sciences. She is a member of the Florida Astronomical Society, the Astronomical Society of the Pacific, the Planetary Society, and the Southeastern Geological Society.

The author's immediate plans include publication of the results of her dissertational research in an astronomical journal, execution of the spectroscopic research proposed in her dissertation, and continuation in her capacity as the astronomer-physicist at SFCC. In the near future she intends to complete, from her previously conceived outlines, several writing, video-tape, visual-aid, and research projects in astronomy, physics, and grammar. She will continue her formal education by enrolling in classes in geology, meteorology, physics, mathematics, and dancing. She also intends to shift her career emphasis from classroom instruction to writing and research, and tentatively plans to apply for a position as an astronaut-specialist, possibly for a Mars mission.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Frank Bradshaw Wood, Chairman
Professor of Astronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

John P. Oliver
Associate Professor of Astronomy

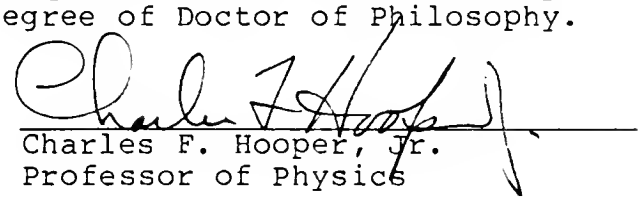
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Howard L. Cohen
Associate Professor of Astronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Alex G. Smith
Professor of Astronomy

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



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This dissertation was submitted to the Graduate Faculty of the Department of Astronomy in the College of Liberal Arts and Sciences and to the Graduate School, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August, 1983

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